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ROUTLEDGE

The Clean Hydrogen Economy and Saudi Arabia

Domestic Developments and International Opportunities

Edited by Rami Shabaneh, Jitendra Roychoudhury, Jan Frederik Braun, and Saumitra Saxena

"Saudi Arabia is leading the implementation of green hydrogen worldwide, a remarkable feat. This book provides valuable strategic insights into domestic hydrogen governance and its key stakeholders. It analyses the role of Saudi Arabia in future global hydrogen markets. It also shows how targeted research and development can serve the large-scale penetration of clean hydrogen in the Kingdom. These three key aspects provide an essential context for anyone who wants to better understand the nascent global clean hydrogen economy".

–Dolf Gielen, *Senior Energy Economist and Hydrogen Lead, The World Bank*

"Should the global market for clean hydrogen develop, the Saudi 'energy Kingdom' is well positioned to gain a first-mover advantage. But many questions remain unanswered as our knowledge of the market, economics, and technicalities of hydrogen, to name but a few is still at an infant stage. The value of this book resides in answering these questions; it is the first comprehensive and detailed repository addressing the subject from its main facets; within Saudi Arabia and internationally".

–Dr Carole Nakhle, *Chief Executive Officer, Crystol Energy*

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THE CLEAN HYDROGEN ECONOMY AND SAUDI ARABIA

This book provides a first-of-its-kind analysis of the emerging global hydrogen economy from the vantage point of one of the world's biggest energy providers: Saudi Arabia. In 2021, and within the context of the Circular Carbon Economy framework, Saudi Arabia announced its goal to reach net-zero carbon emissions by 2060 and produce a substantial amount of clean hydrogen annually by 2030. The Kingdom is optimally situated geographically between the major demand markets in Europe and North Asia, from where it can leverage clean hydrogen exports as a potential tool to become a player of strategic importance and successfully diversify its economy under its Vision 2030 program. More broadly, the book charts a course for fossil fuel-exporting countries such as Saudi Arabia to carve a competitive position for themselves over the forthcoming decades using clean hydrogen as a catalyst for the energy transition.

With contributions from global energy experts, the chapters in this book provide a multifaceted analysis of the "who," "what," "where," and 'why' related to clean hydrogen development within and beyond Saudi Arabia. Collectively, the contributions analyze the countries and regions relevant to Saudi Arabia in terms of dedicated hydrogen policies, projects, and approaches that aim to incentivize production and demand in an increasingly carbon-constrained world. The book is a timely, unique and an indispensable resource for practitioners and students of energy, geopolitics, and climate policy working on hydrogen in academia, applied research, national government bodies, and international organizations.

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FOREWORD

As the world navigates the energy transition, it has become abundantly clear that there is no single pathway to net zero. All low-carbon technologies must be explored and deployed to reach carbon neutrality while limiting tradeoffs in economic growth, energy security, and affordability. Clean hydrogen and its derivatives are being recognized as one of the solutions, particularly for sectors of the economy that are hard to electrify. The use of hydrogen as an energy carrier has garnered unprecedented support, and many countries have released or are developing hydrogen strategies and roadmaps to explore how hydrogen fits into their existing energy systems. Its future deployment, however, is highly contingent on the proper regulation and policies to be implemented and the cost trajectory of hydrogen production and end-use technologies.

The Kingdom of Saudi Arabia aspires to be a significant player in the fast-evolving clean hydrogen market. The Kingdom has started implementing priority actions across the clean hydrogen supply chain by forging government-to-government and corporate partnerships, developing demonstration and commercial supply projects and piloting domestic end-use cases. Other countries are also stepping up efforts to look at hydrogen as an energy carrier to meet their national climate targets. This could lead to a globally traded commodity bringing with it monetization of new local resources, new cross-border trade relationships, knowledge-based competition, and opportunities for job creation.

Given their mandate and expertise, the King Abdullah Petroleum Studies & Research Center (KAPSARC) and King Abdullah University of Science and Technology (KAUST) have initiated this first-of-its-kind book which brings together international experts to analyze the developments in the potential clean hydrogen market and what it means for the Kingdom. It provides a technical assessment of hydrogen-related technologies and underscores the important role of technology and technical institutions in advancing the hydrogen economy. The collaborative approach between different think tanks, academic institutions, and the public and private sectors reflected in this book exemplifies the collaborative efforts needed to reach net-zero targets in a timely and cost-effective manner.

Fahad Alajlan & Dr. Tony F Chan

1

THE CLEAN HYDROGEN ECONOMY AND SAUDI ARABIA

Introduction

Jan Frederik Braun, Rami Shabaneh, Saumitra Saxena, and Jitendra Roychoudhury

Clean hydrogen (i.e., renewable, nuclear, and fossil gas-based hydrogen variants with extremely low methane emissions and high carbon capture rates) is generally regarded as an essential piece of the energy transition to meet the world's climate goals set in the 2015 Paris Agreement. Since the Paris agreement, hydrogen has garnered unprecedented support from governments and industries as a primary solution to complement electrification and reduce emissions in hard-to-abate sectors. Japan was the first to pursue a national hydrogen strategy and integrate hydrogen into its existing energy system when it adopted its *Basic Hydrogen Strategy* in 2017. Since then, dozens of countries have followed suit and a substantial number of others are currently preparing strategies.

As Saudi Arabia and the other Gulf Cooperation Council (GCC) countries continue their ambitious plans to diversify their economies away from oil and gas, the Gulf region is showing a growing interest in developing a clean hydrogen sector. Saudi Arabia is well positioned to become a global producer, consumer, and exporter of clean hydrogen and its derivatives. The Kingdom has the natural resources, existing industrial capacity, and geographical proximity to growing energy markets to scale up its clean hydrogen infrastructure and markets (Box 1.1).

Fully leveraging clean hydrogen to sustainably power the global economy would give Saudi Arabia a competitive edge in an increasingly carbon-constrained world in which net-zero greenhouse gas emissions are both a requirement and a condition for survival. This should be combined with the large-scale electrification of the key sectors of the economy and carbon capture, utilization, and storage (CCUS); hydrogen is therefore one of the Kingdom's main pillars in meeting its net-zero emissions pledge by 2060.

This book provides a first-of-its-kind analysis of the emerging global hydrogen economy; further, it presents the opportunities and challenges for a range of

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BOX 1.1 SAUDI ARABIA'S CLEAN HYDROGEN RESOURCES

Renewables-based hydrogen

- Lowest global renewables electricity prices and ample solar and wind in the Kingdom.
- Large availability of non-arable land areas suitable for the development of renewable projects.

Natural gas-based hydrogen

- Around 233.8 trillion cubic feet (or 6.6 trillion cubic meters) of low-cost natural gas available, suitable for producing blue hydrogen.
- Storage capacity potential of 25 Gt of CO_2 (with 90% of the deep saline formations in the Middle East), suitable for producing blue hydrogen (Ward and Heidug 2018).

Hydrogen export

- Existing infrastructure to export hydrogen in the form of ammonia and other hydrogen derivates globally.
- Strategic location with trade routes for energy products from Saudi Arabia to European and Asian markets.

Potential domestic uses

- Decarbonize the existing base of ammonia and methanol plants.
- Use in heavy-duty transport and high-utilization public transport vehicles.
- Produce green steel via hydrogen-based direct reduced iron.

Source: Authors.

potential exporters and importers from the vantage point of Saudi Arabia. The Kingdom is already one of the world's largest energy providers. With contributions from key national and international stakeholders, including governments, industry partners, and academia, this book aims to answer the following central questions:

- What are the challenges and opportunities for Saudi Arabia in the domestic and international fields of clean hydrogen?
- Which countries and regions relevant to Saudi Arabia are working on clean hydrogen and for what purposes?
- How can the technological gaps in the commercial-scale penetration of clean hydrogen in Saudi Arabia be bridged by targeted research, development, demonstration, and innovation (RDD&I)?

Based on several strategic advantages and resources, Saudi Arabia could carve out a competitive position as a premier producer, consumer, and exporter in the nascent global clean hydrogen market. This ability provides the Kingdom with the option to leverage its high-quality resources for low-cost production, diversify its energy and commodity exports, attract investment in hydrogen projects, and create structural economic value at home. In pursuing this unique opportunity, it has its work cut out to fully capitalize on its potential. Major challenges include the fact that some technologies for making clean hydrogen are mature but expensive; therefore, they need to be deployed on a large scale to lower costs and compete with traditional fuels. In addition, the development of new applications and infrastructures for hydrogen must be ramped up to meet the uptake in hydrogen demand and accelerate market formation.

Internationally, the multiple pathways through which clean hydrogen can be produced allow countries to increasingly become energy self-sufficient. Moreover, such pathways also facilitate countries, including traditional energy importers, to join the race for international export markets, thereby adding a different level of competition. However, a global standard for clean hydrogen is yet to be established; this includes a universally accepted methodology for accounting and verifying CO_2 emissions. This may pose investment risks for large potential exporters such as Saudi Arabia and a barrier to market entry. Domestically, the government must strive to formulate clean hydrogen policies, regulations, infrastructure plans, and technological and financial enablers.

The remainder of this Introduction is structured as follows. The first section assesses the hydrogen economy, including its state-of-the-art within and beyond the Kingdom. This section also provides conceptual clarity by defining the hydrogen topics central to this book. The second section describes clean hydrogen's momentum and how this differs from early instances in the 1970s and early 2000s. In terms of approach, ambitions, opportunities, and challenges, the third section focuses on Saudi Arabia's current and possible future role in the hydrogen economy. The fourth section offers insights into the statement of the aims of this book to provide a general clean hydrogen economy roadmap that is central to our analysis. The final section introduces the structure of the book, mentioning its three parts and various chapters.

Definition of the hydrogen economy

The term 'hydrogen economy' was introduced in the literature in 1972 by a Professor of Chemistry, named John O'Mara Bockris (Bockris 1972). In the paper titled *The Hydrogen Economy: An Ultimate Economy?*, Bockris and his co-author John Appleby explained how hydrogen is made and its costs at the time; they further described a system in which the world could depend on hydrogen, similar to how it depended on gasoline at the time (Bockris and Appleby 1972). Bockris later defined the hydrogen economy as a system within which the industry, transportation, and households could depend on 'piped hydrogen' as a fuel that can be transported over long distances from 'large atomic or distant solar sources' (Bockris 1977).

Bockris' definition of the hydrogen economy was clearly presented in the context of the macro- and geo-economic circumstances of that time. Indeed, he argued that the use of atomic and solar-produced hydrogen would reduce energy costs; this would further start a journey toward overcoming the high price of hydrocarbons from Middle Eastern sources, following the first oil crisis in 1973 (Bockris 1977).

More recently, the term 'hydrogen economy' has expanded to cover the commercial use of low-carbon hydrogen in all suitable economic sectors, including such end-use applications as heavy-duty road transport, ships, trains, and aircraft (The Economist 2020; Kufeoglu 2023). This definition suggests that clean hydrogen can also be used as a source to heat buildings, store surplus electricity from solar and wind, and reduce iron ore for steelmaking. The society-wide implementation of hydrogen as an energy carrier (i.e., a way to store, move, and use the energy extracted from other sources), feedstock, or storage medium could help establish a hydrogen economy. This hydrogen economy will come to dominate daily life in the way that fossil fuels currently do.

These basic definitions provide a good starting point to explain what we understand by the term 'hydrogen economy' in this book. First, this book explores the variety of clean hydrogen production pathways. It thus extends the transport focus from pipelines to include different modes of transporting hydrogen such as shipping, either in its pure form, or in liquid organic hydrogen carriers (LOHCs), and hydrogen-based derivatives such as ammonia and methanol. Second, this book argues that hydrogen will not be the new oil or gas, as it is a conversion and not an extraction business and can be produced anywhere in the world via electrolysis. Third, government support is required to kickstart the development of hydrogen; additionally, public funding is needed to create the necessary infrastructure and promote use cases via financial incentives. Simultaneously, major projects and large-scale production and consumption hydrogen hubs concentrated in specific geographical areas will push governments to implement suitable policies and regulations. The market will initially be determined by long-term contracts and scaling up production capacity. There is significant room for cost efficiency gains and RDD&I in hydrogen-based services and applications along the value chain. The hydrogen value chain broadly covers production; supply, distribution, and storage; and end uses (Figure 1.1).

Fourth, hydrogen policy will be defined by specific greenhouse gas emissions and sustainability criteria (i.e., gCO_2 per kWh of hydrogen). These criteria, captured in standards and certification schemes, will define and ensure that the hydrogen produced adheres to the definitions and labels assigned to it.[1] In the case of hydrogen, a standard is needed to provide the accounting guidance and criteria to assess renewable and low-carbon credentials. Moreover, certificates for hydrogen and its derivatives would contain information on compliance with these standards and regulatory requirements. This would enable verification by independent third parties (or agencies) using data on sustainability criteria such as carbon footprint and renewable energy content; this would allow differentiation from less green products (IRENA and RMI 2023).

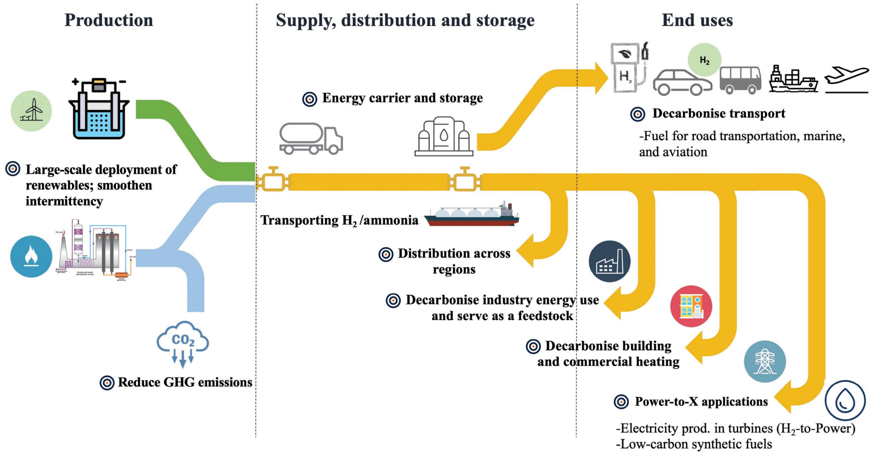

FIGURE 1.1 The hydrogen value chain.

Source: Hasan and Shabaneh (2021).

Fifth, synergies with electricity will be strong, as hydrogen will complement electricity in the energy transition. This means that hydrogen has a range of potential applications within the industrial, transport, energy storage, and heating sectors in which electrification is either too costly or impossible to apply. However, hydrogen is not the only solution to climate change and will have to compete with the other decarbonization solutions in each sector, such as direct electrification and biomass.

Finally, for the major demand centers in the United States and Europe, the incentives for clean hydrogen are framed in the broader policy narratives of the energy transformation, economic growth, diversification, innovation, and adaptation to new global competitive requirements. Clean hydrogen is narrowly defined, not only in terms of scaling up its production and demand as a feedstock or energy carrier but also as part of a range of options, including increasing energy efficiency, electrification, and circularity.

Based on these assumptions, we argue that the hydrogen value chain will retain some of the features of liquefied natural gas and electricity. At the outset, governments will play an important role in formulating the hydrogen policy and financing the basic hydrogen infrastructure. However, the value chain will eventually evolve to have unique characteristics, with pricing and quality signals emanating from end-use customers, as the hydrogen market gets established (i.e., end-use-related services and applications). This could mean that in an established hydrogen market, the hydrogen value chain will be demand-driven, with energy end-use consumers playing an important role (Figure 1.2).

This does not mean we ought to disregard or deny the value of hydrogen production. Recent discussions have focused on scaling up hydrogen production and demand to establish economies of scale and reduce costs. In the long run, however,

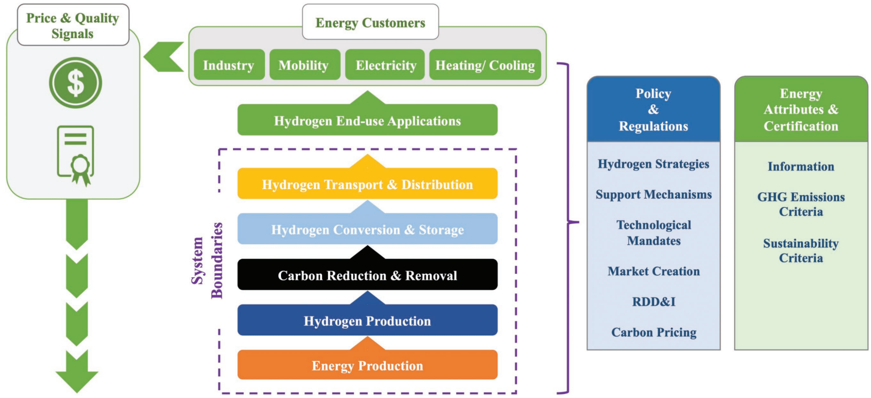

FIGURE 1.2 Customer-centered hydrogen economy supply chain.

Source: Wa‘el Almazeedi.

the differences in the cost of producing a kilogram of hydrogen will become minimal between countries. A country or region's ability to carve out a competitive position and capture value in the hydrogen economy will lie in its capacity to produce high quality, cost-competitive, and innovative hydrogen equipment and components along the value chain. The estimation of the market potential for hydrogen equipment and components by 2050 shows that value creation will largely lie in the end-use sector such as transport and industry (Box 1.2).

BOX 1.2 ESTIMATED MARKET POTENTIAL FOR HYDROGEN EQUIPMENT AND COMPONENTS BY 2050

Production	Distribution and storage	(Re-)conversion*	End use	
USD 60-65 bn	USD 25-30 bn	USD 35-40 bn	USD 80-90 bn	
			Transport	Industry
USD 50-60 bn for electrolyzers	USD 5-7 bn for storage	USD 21-25 bn for ammonia	USD 21-25 bn for fuel cells	USD 16-20 bn for iron reduction and electric arc furnace
USD 5-7 bn for capture technology	USD 5-7 bn for compression	USD 16-20 bn for carbon-based compounds (e.g., methanol, synfuels)	USD 11-15 bn for onboard storage	USD 11-15 bn for equipment
			USD 8-10 bn for combustion engines	USD 8-10 bn for heat and power generation
	USD 2-5 bn for pipelines		USD 3-6 bn for fueling stations	
	USD 11-15 bn for other distribution			

Calculations are based on the International Energy Agency's IEA's Sustainable Development Scenario, which models a rapid and deep transformation of the global energy sector consistent with all the net-zero goals contemplated today and being reached on schedule and in full. Values are for the annual capex market size for equipment and components needed to switch to green or blue hydrogen applications (including retrofits), not including revenues that companies may achieve by operating hydrogen equipment or providing green energy as an input for electrolysis. *) Assumes that 5% of hydrogen that is not produced onsite is converted to ammonia, methanol, or LOHCs.

Source: Authors based on Ludwig et al. (2021).

Although hydrogen is a colorless and odorless gas, the hydrogen produced via different methods has been informally color coded to differentiate the intensity of carbon emissions, as explained in Figure 1.3. However, while this color coding is generally accepted, no universal convention has evolved yet.

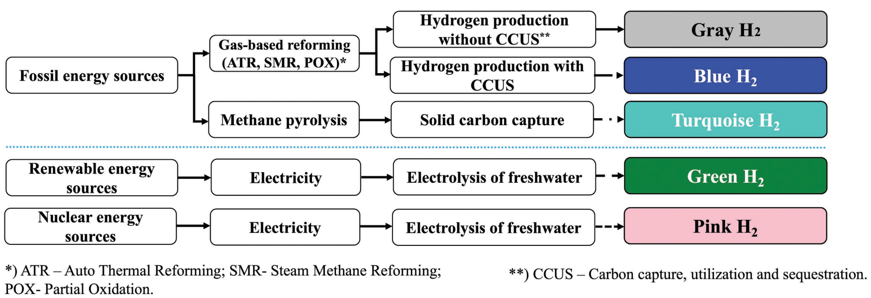

FIGURE 1.3 Colors of hydrogen.

Source: Authors.

For the purpose of this book, we use these color codes to signify the production process. However, the proliferation of hydrogen colors is complicating the discussion because of the increasing focus on carbon intensity and carbon equivalence in addition to color (IEA 2023a). Carbon intensity, expressed in tons of CO_2-equivalent per ton of hydrogen produced, is a technology-neutral criterion for assessing the hydrogen emission footprint. It focuses on tackling fugitive emissions and opens the debate about the competition between various hydrogen production approaches that meet the required carbon intensity at the lowest cost. Thus, throughout this book, we define 'clean hydrogen' in two ways. The first is the hydrogen derived from the electrolysis of water with electricity coming from renewable sources and nuclear energy. The second is the hydrogen derived from production processes in which CO_2 emissions are captured (Box 1.3).

BOX 1.3 HYDROGEN DEFINITIONS USED IN THIS BOOK

Definitions used in this book

- **Clean hydrogen** refers to renewable, nuclear, and fossil gas-based hydrogen (with the latter's methane emissions being extremely low and with very high carbon capture rates).
- **Blue hydrogen** refers to fossil gas-based hydrogen with CCUS and that meets certain emission standards.
- **Gray hydrogen** refers to hydrogen produced from fossil fuels without capturing greenhouse gas emissions in the process.
- **Green hydrogen** refers to hydrogen produced with renewable electricity via electrolysis.
- **Hydrogen derivatives** refer to downstream molecules into which hydrogen can be converted (e.g., ammonia, methanol, and synthetic fuels). When these products are produced with hydrogen from electrolysis, they are known as power-to-X products.
- **The hydrogen economy** constitutes either a regional or a global energy marketplace that complements that of electricity and plays a role in decarbonizing those parts of societies that electrification cannot. As a complement, the hydrogen supply chain will be linked closely to that of electricity, and most value will be created in the end-use sector in the long term.
- **Hydrogen hubs**, or clusters or 'valleys' of large-scale demand, are local areas in which various existing and potential hydrogen users from differing sectors are co-located. The co-location within hubs can make it more cost-effective to develop infrastructure (e.g., pipelines, storage, and refueling stations) by promoting economies of scale and synergies from sector coupling to help develop the value chain.
- **Synthetic fuels** refer to a variety of gaseous and liquid fuels produced from hydrogen and CO_2, preferably captured from an emitting source or air, including synthetic kerosene and synthetic diesel.

Source: Authors and World Energy Council (2021).

Hydrogen's 'third coming' in a carbon-constrained world

Hydrogen has seen several waves of interest over the last 50 years. In the 1970s, with oil price shocks, petroleum shortages, and rising attention to air pollution and acid rain, hydrogen produced from coal or nuclear electricity was considered to play an important long-term role in providing energy, particularly for transport. This interest waned as oil and gas resources proved plentiful, oil prices stabilized, and nuclear power faced increasing public resistance. In the early 2000s, interest in hydrogen resurfaced, which translated into renewed policy action in the transport sector. By 2010, however, expectations had dipped again with the retreat of the peak oil narrative, uncertainty about the strength of climate policy developments, and progress with battery electric vehicles, which have less expensive initial infrastructure needs than hydrogen vehicles (IEA 2019).

Hydrogen's 'third coming' is markedly different from the two previous waves of interest. Whereas the first and second waves focused largely on the use of fuel cells in the transport sector, the current momentum is characterized by much broader possibilities for hydrogen use and a depth of political enthusiasm for those possibilities globally. Hydrogen is increasingly a staple of mainstream energy conversations in most regions, with diverse countries and industry stakeholders seeing it as playing a potentially valuable and wide-ranging role in an increasingly carbon-constrained world (IEA 2019). The broad coalition of stakeholders includes the governments of most of the world's largest economies (including Saudi Arabia), renewable electricity suppliers, industrial gas producers, electricity and gas utilities, automakers, oil and gas companies, and major engineering firms.

The three main drivers of hydrogen's current momentum are the

- i Accelerating climate change
- ii Declining cost of renewables
- iii Improving national energy security

Regarding **climate change (i)**, in the post-Paris Agreement world, there is broad consensus that hydrogen will be needed to reach net-zero emissions and mitigate catastrophic climate change. Hydrogen demand reached 94 million tons in 2021, mainly for traditional uses such as a feedstock for making chemicals (e.g., ammonia and methanol) and an input in the oil refining sector to desulfurize and upgrade refined products. New applications, mostly in on-road transport, comprised only 0.04% of hydrogen demand in that year (40 thousand tons) (IEA 2022). Most of this demand was met by gray hydrogen, which translated into emissions of about 900 million tons of CO_2/year, equivalent to 2.2% of energy-related CO_2 emissions globally (IEA 2022).

Cleaner production pathways for hydrogen are needed to lower its carbon footprint and become a genuinely low-carbon solution. Mature technologies for producing low-carbon hydrogen are expensive and would need to be deployed on a large scale to lower costs sufficiently to compete with traditional fuels. By contrast, the development of new hydrogen applications and infrastructure must be ramped up to meet the uptake in hydrogen demand and accelerate market formation. However, in the absence of a hydrogen price benchmark, government support through various regulatory and financial interventions will be needed, along with sound business models, to de-risk investments and incentivize the adoption of hydrogen. Moreover, estimations of how much hydrogen the world will need are mixed depending on the prevailing decarbonization policies and cost of hydrogen technology. Hydrogen demand is projected to be anywhere between 4% and 24% of the final energy supply by 2050 (Figure 1.4a).

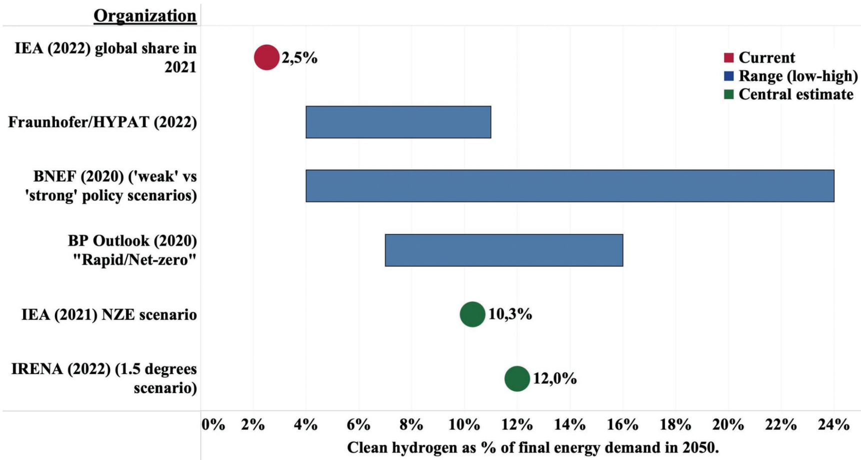

FIGURE 1.4A Global final energy supply and share of clean hydrogen (2021 vs. 2050).

Source: Authors based on IEA (2021, 2022), Riemer et al. (2022), Evans and Gabbatiss (2020), and IRENA (2022b).

Regarding future demand in a net-zero world, governments and industry players worldwide currently consider clean hydrogen and its derivatives to play three overarching roles:

- Decarbonize hard-to-abate segments of the energy value chain that cannot be easily electrified.
- Enable sector coupling by integrating the electric power sector with the heating and cooling, transport, and industrial sectors.
- Facilitate fuel switching, including retrofitting and modifying infrastructure, and new use applications (i.e., where new infrastructure must be established).

With these roles in mind, hydrogen demand is expected to take off massively over the next three decades (Figure 1.4b).

From the vantage point of the 1.5°C scenario, if clean hydrogen could satisfy 12% of final energy demand, it could reduce global emissions by 10% (IRENA

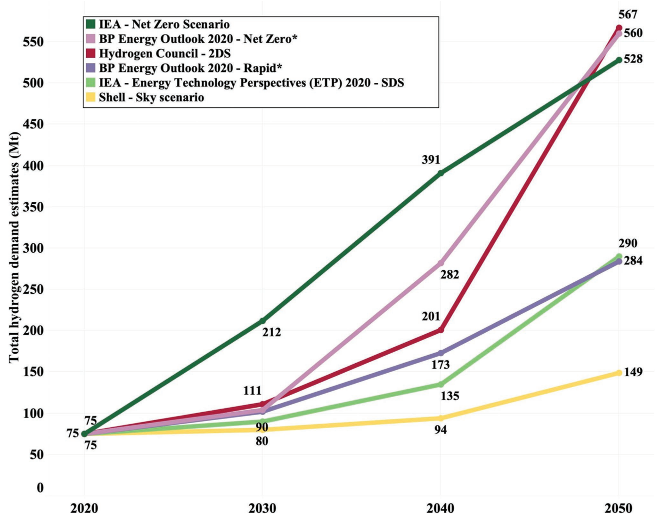

FIGURE 1.4B Global hydrogen demand scenarios 2020–2050 (total demand for energy and non-energy usages).

Source: Authors based on World Energy Council (2021*). The BP numbers include the World Energy Council's estimates of non-energy demand.

2022b). In this scenario, Saudi Arabia would constitute the country with the sixth highest domestic hydrogen demand by 2050, after China, India, the United States, Russia, and Japan (Figure 1.4c).

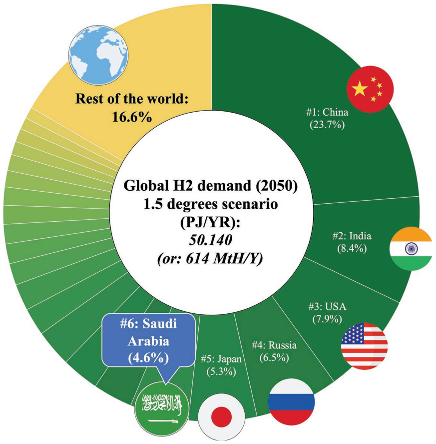

FIGURE 1.4C Global hydrogen demand by 2050 in the 1.5°C scenario (excluding use for power generation).

Source: Authors based on IRENA (2022b).

Figure 1.4c points to the important role that clean hydrogen should play in decarbonizing the world's major economies. In the case of Saudi Arabia and the other countries mentioned here, clean hydrogen can decarbonize oil refining and fertilizer production, make synthetic kerosene for planes and methanol for ships, and replace natural gas in making steel from iron ore. These 'hydrogen products' are easy to transport and have ready end-user markets.

In sum, Figures 1.4a–c examine global hydrogen demand and supply from different angles, including from percentages and millions of tons as well as the role that hydrogen could play in reducing emissions in a 1.5°C world. These figures show the massive range in the different scenarios designed by well-known public and non-public actors and underline the vast uncertainty about this nascent market.

Regarding the **cost of renewables (ii)**, hydrogen's 'new wave' broadly focuses on creating a link between renewable electricity and hard-to-electrify end-use sectors (IRENA 2020). The competitiveness of renewables improved exponentially from 2010 to 2021. As shown in Figure 1.5, the global weighted average levelized cost of energy of newly commissioned utility-scale solar photovoltaic projects declined by 88% between these years. By contrast, that of onshore wind fell by 68%, concentrated solar power by 68%, and offshore wind by 60% (IRENA 2022d).

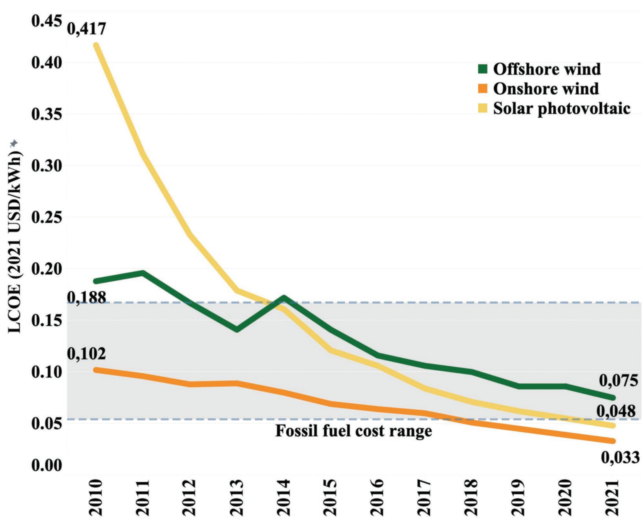

FIGURE 1.5 Global levelized cost of energy of newly commissioned utility-scale solar photovoltaic and onshore and offshore wind power, 2010–2021.

Source: Authors based on IRENA (2022c).

The fall in electricity prices because of renewables is also complemented by declining electrolyzer costs because of technology improvements and efficiency gains. Electrolyzer technologies are ripe both for innovation and for economies of scale. They may well be the next technology to shoot down a precipitous cost curve in the way that solar cells and batteries have. The recent successes of solar photovoltaic, wind, batteries, and electric vehicles have shown that policy and technology innovation have the power to build global clean energy industries. With a global energy sector in flux, the versatility of hydrogen is attracting stronger interest from the diverse group of stakeholders mentioned earlier.

The global energy crisis sparked by the Russia/Ukraine conflict that began in early 2022 has accelerated hydrogen's appeal as an energy carrier that can improve **energy security (iii)**. This is defined as the uninterrupted availability of energy sources at an affordable price (IEA 2023b). Long-term energy security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the contrary, short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply-and-demand balance. Clean hydrogen could bolster energy security in three major ways: (1) by reducing import dependence, (2) by mitigating price volatility, and (3) by boosting energy system flexibility and resilience (IRENA 2022a). Many governments, particularly in Europe, are looking at hydrogen to reduce their dependency on fossil fuels. They also believe that hydrogen can diversify fuels to improve the flexibility of the energy system and reduce its vulnerability to supply disruptions as well as diversify supply to become significantly larger than that of current fossil fuel suppliers.

A multitude of factors influence the assessment of the role of hydrogen as a clean energy vector in improving energy security (IEA 2022). In regions in which fossil fuel resources are limited and often imported, as in Japan and South Korea, renewable hydrogen is well placed to improve energy security. Importing blue hydrogen, on the contrary, would raise fossil fuel imports as well as the dependency on a limited portfolio of suppliers. In regions and countries with significant fossil fuel resources such as Australia, North America, and the Middle East, the production of low-carbon hydrogen is unlikely to pose a risk to their national energy security. In Europe, importing hydrogen from a range of diverse and reliable partners to replace Russian fossil fuels would enhance energy security even if the imported hydrogen had been produced from fossil fuels (with CCUS). Additionally, having a strong national capability in hydrogen may be of significance to importers as in Europe beyond the core focus on net zero. This need to import offers enormous opportunities to clean hydrogen producers in the Gulf such as Saudi Arabia. Indeed, the Kingdom has strengthened its political and economic ties with Europe in this field through a range of government-to-government and business-to-business agreements, for example with Germany (Braun et al. 2022).

Saudi Arabia's Circular Carbon Economy (CCE) and clean hydrogen

Clean hydrogen plays a leading role in the Kingdom's CCE framework. The CCE, which was introduced by His Royal Highness (HRH) King Salman at the end of Saudi Arabia's 2020 G20 presidency, extends the idea of a circular economy but its primary focus is on energy and carbon flows (Figure 1.6).

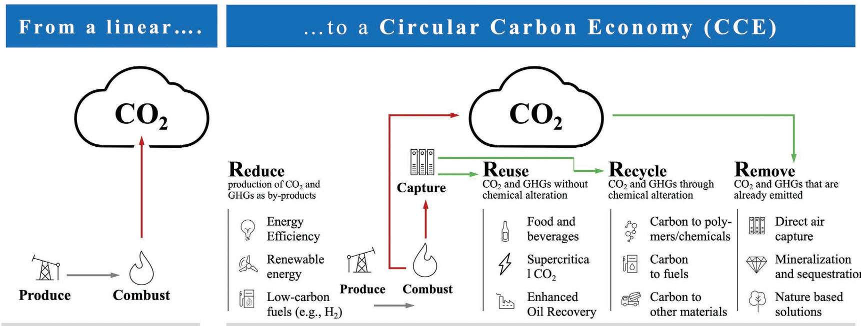

FIGURE 1.6 Saudi Arabia's CCE approach.

Source: Al-Ghareeb (2022).

Instead of removing carbon emissions altogether in the medium-to-long term, the CCE approach focuses on commodifying carbon emissions. In other words, it aims to reframe the discourse on CO_2 from being viewed solely as a negative externality toward understanding the value that can be extracted from it. The CCE climate mitigation approach therefore focuses on managing the carbon inherent in human activities, industrial enterprises, and energy systems in a sustainable and cyclical manner. Box 1.4 defines one of the conceptualizations of the CCE and its organizing principles, namely, the four Rs of Reduce, Recycle, Reuse, and Remove (Al Shehri et al. 2022).

BOX 1.4 CONCEPTUALIZATION OF THE CCE

Reduce	*Recycle*	*Reuse*	*Remove*
Minimizing fugitive carbon by employing energy efficiency, nuclear energy, and fuel switching	Minimizing fugitive carbon by encouraging mitigation through living carbon using bioenergy and natural sinks	Reusing captured carbon through carbon utilization and converting CO_2 into durable carbon, including building materials and polymers	Storing captured carbon by converting CO_2 into durable carbon via enhanced oil recovery, bioenergy with carbon capture and storage, and direct air capture (and removals via natural sinks)

Source: KAPSARC (2020).

The approach has, however, raised questions given Saudi Arabia's past positions on global climate change (Depledge 2008). An early critical voice described the CCE as 'a renewed push' for CCUS technologies. Schroeder, Bradley, and Lahn (2020) argued that removing state support for fossil fuels and putting a price on emissions is largely agreed as the most cost-effective way to ensure that CO_2 is removed from the system permanently. Even the authors who raised this concern, though, recognized that developing the capacity to remove CO_2 makes sense for countries such as Saudi Arabia and the United Arab Emirates (UAE). As these nations heavily depend on oil exports and have large vertically integrated industries, they wish to make their exports as low carbon as possible. This is especially so given growing market pressure from consumers, particularly in Europe, to reduce lifecycle emissions. In this context, it is important that the CCE concept is implemented by a clear and effective regulatory framework and policies that prove its potential beyond CCUS as well as beyond political endorsement by international organizations such as the G20. The launch of Saudi Arabia's national CCE program could demonstrate the concept's application in practice. A clearly defined CCE taxonomy and its consistent use in this program could also help provide conceptual clarity and a blueprint for other countries' practical implementation (Al Shehri et al. 2022).

The Saudi government views hydrogen applications as a critical and crosscutting component of the CCE, especially as a key enabler in decarbonizing hard-to-abate sectors:

- Reduce: Renewables-based hydrogen without directly emitting CO_2.
- Recycle: Renewables-based hydrogen is used to produce e-fuels, thus recycling CO_2 through chemical alterations.
- Reuse: CO_2 is captured during fossil fuel-based hydrogen production and reused in applications such as carbon-cured concrete.
- Remove: CO_2 is captured during fossil fuel-based hydrogen production and removed through geologic storage.

In 2021, Saudi Arabia announced its goal to reach net-zero carbon emissions by 2060 and produce 4 million tons of clean hydrogen annually by 2030 (Saudi Green Initiative 2022). Furthermore, domestic oil giant Aramco has set a target to produce 11 million tons of blue ammonia by 2030. This would require 1.93 million tons of blue hydrogen produced from fossil gas linked to carbon capture and storage. Saudi Arabia has also developed a national hydrogen strategy that focuses on the production, export, and domestic use of clean hydrogen (Braun et al. 2022), as shown in Figure 1.7.

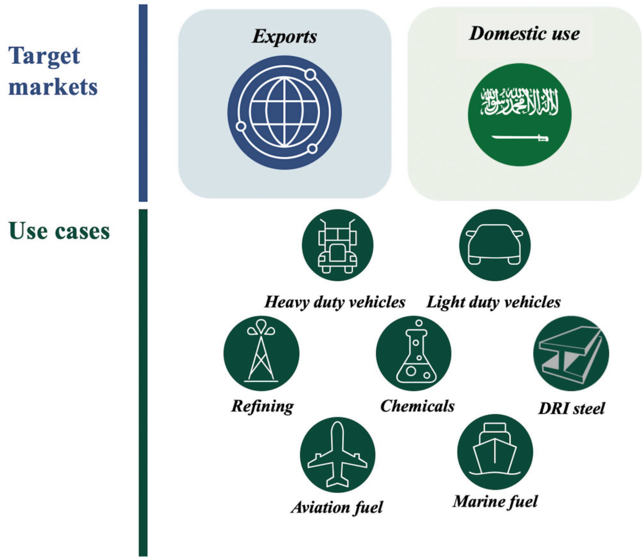

FIGURE 1.7 Saudi Arabia's target markets and use cases for hydrogen.

Source: Al-Ghareeb (2022).

By 2030, the strategy aims to:

I Establish the essential aspects of the green and blue hydrogen production processes.
II Build domestic hydrogen demand use cases in transportation (e.g., heavy-duty and light-duty vehicles).
III Use hydrogen in products with export potential (e.g., synthetic fuels and steel).
IV Export hydrogen to potential markets in Europe, Asia, and the rest of the world.

The Saudi focus beyond 2030 aims to build capacity through pilots and R&D, including:

- Hydrogen-based green steel using the direct reduced iron process, including a pilot plant and commercialization expected after 2030.
- Synthetic fuels for aviation that combine hydrogen with CO_2, including R&D (commercialization expected after 2035).
- Ammonia and methanol as marine fuels, which help decarbonize and meet International Maritime Organization regulations, with commercialization expected after 2035.

To support the deployment of clean hydrogen across Saudi Arabia's value chain for domestic use and exports, several enabling mechanisms are being considered:

- Support and enforcement mechanisms for production and usage.

- Investment in RDD&I.
- Standards and technical regulations.
- Awareness and global partnership building across the value chain with countries and regions with major demand (e.g., Europe and Southeast Asia).
- Hydrogen hubs and valleys.

Given its resources, Saudi Arabia can theoretically pursue a solely green or blue hydrogen strategy. Developing both pathways, however, may provide the optimal solution because the Kingdom's geographical spread of resources suggests that the eastern region is better suited to produce and export blue hydrogen. By contrast, green hydrogen production is well suited for areas far from oil and gas clusters such as the western region in which the economic region of NEOM is taking shape.

NEOM (Chapter 5), an acronym that combines the Greek *neos* ('new') and the first letter of the Arabic word for 'future,' *mustaqbal*, will be a prominent part of any future Saudi hydrogen ecosystem. As a hydrogen hub, its goal is to provide the basis for the clean feedstock used in the global production of fertilizers, chemicals, and oil derivatives. The region's electricity supply will be 100% renewables-driven, including the multiple gigawatts required for the vast green hydrogen production in the floating industrial city in the shape of an octagon called 'OXAGON'.

Regarding Saudi Arabia's hydrogen economy governance, Chapter 2 makes the argument for the Kingdom to pursue parallel strategies or a balanced approach. Most of the country's production, demand, and infrastructure for blue hydrogen are in its eastern and central provinces. By contrast, the area that holds the most promise for green hydrogen (i.e., the northwest of the Kingdom) shows little to no industrial-scale production, demand, and infrastructure requirements, which will quickly need to be built from scratch. Instead of an exclusive focus on any one of the production methods, a balanced approach between renewable and low-carbon hydrogen production and demand can reduce the burden on land use and resources and provide the time to overcome infrastructure challenges. A final argument for a balanced approach is that Saudi Arabia possesses both low-cost renewable and gas resources that could produce the volumes of hydrogen needed to both decarbonize its sectors and have sufficient available for export.

In addition, this book foresees that the hydrocarbon-derived and low-emission hydrogen pathway has salience in nations such as Saudi Arabia that have significant hydrocarbon reserves and CO_2 injection/storage potential as well as an interest in preserving the value of those resources. The challenge is to have low fugitive methane emissions and a high CO_2 capture rate. Supplementary to costs, Saudi Arabia has the capital and regulatory capability to compete on these highly important decarbonization issues.

Finally, the opportunities from adopting a balanced approach extend beyond Saudi Arabia's borders. Along with other GCC countries, Saudi Arabia can attain economies of scale and pool human, capital, and technical resources in a cost-efficient manner (e.g., via regional CCUS and hydrogen hubs). In this way, it can benefit immensely from scaling up production, cooperation, national demand, and cross-border infrastructure and focus (in the long run) on the production of clean hydrogen-based end products. This will allow for the localization of know-how and skills along the value chain.

Although Saudi Arabia is well positioned to become a significant global hydrogen player, it also faces several substantial challenges, including:

- Drastically scaling up clean hydrogen production and dedicated renewables capacity.
- Creating the required sectoral demand by formulating an effective framework of regulations and policies.
- Facilitating finance.
- Developing the required policies and regulations (e.g., infrastructure, certification, and sustainability criteria).
- Bridging the knowledge gap in RDD&I and establishing a resilient domestic capability in equipment manufacturing for energy customers in the end-use segment, including the demonstration of technologies for local and international markets.
- Addressing geopolitical factors such as shifts in inter-state relations and the fact that hydrogen rents (or 'revenues') may not be as lucrative as those of oil and gas.

The Saudi government has already started to prioritize building government-to-government partnerships, supporting large-scale projects, carrying out feasibility studies for developing an infrastructure to export hydrogen or renewable energy, establishing a regulatory framework, and introducing enablers to expedite hydrogen-related investment. These and other efforts that will need to be scaled up rapidly over the forthcoming years could allow the Kingdom to establish the institutional capability required for two actions. The first is to develop a competitive hydrogen economy at home and the second is to allow the country to capture a substantial share of any future hydrogen market overseas.

Statement of aims and conceptual framework

Collectively, the chapters in this book provide a multifaceted and impartial analysis of the 'who,' 'what,' 'where,' and 'why' related to clean hydrogen development within and beyond Saudi Arabia. They analyze the countries and regions relevant to Saudi Arabia in terms of dedicated hydrogen policies, projects, and approaches that aim to incentivize production and demand. This will enable the design of financing and business models, ensure a proactive role for the private sector, and facilitate the development of hydrogen hubs. Some of the key issues discussed in this book include the following:

- Understanding domestic policy developments in Saudi Arabia that strengthen its position in global hydrogen markets and that promote economic diversification.
- Explaining the hydrogen value chain in the Kingdom (i.e., production, CCUS, storage and distribution, consumption, and exports) and its critical role within the country's CCE approach.
- Examining the potential of hydrogen demand beyond the industrial sector (e.g., transportation, power generation, and storage mechanisms for renewable energy) within the Kingdom.
- Understanding international developments, including potential competing export and import markets in the context of global decarbonization policies and technologies.

In addition to analyzing the hydrogen economy from the Saudi Arabian vantage point, this book simultaneously presents analyses along all parts of a clean hydrogen economy roadmap. This roadmap charts a course for fossil fuel-exporting countries such as Saudi Arabia to carve a competitive position for themselves in the energy transition over the forthcoming decades using clean hydrogen as a catalyst (Figure 1.8). The added value is that this roadmap can be applied to fossil fuel-producing countries other than Saudi Arabia.

The roadmap is divided into seven pillars:

- Scaling up commercially proven state-of-the-art clean carbon hydrogen production technologies.
- Creating local demand applications for clean carbon hydrogen.
- Rolling out the required infrastructure.
- Facilitating financing for clean hydrogen projects.
- Developing policies and regulations for efficient and well-functioning markets for clean hydrogen and its derivatives that allow for trading and matching supply and demand.
- Demonstrating key pre-competitive technologies that could improve the sustainability and reduce the costs of hydrogen applications along the value chain.
- Build a robust in-Kingdom RDD&I ecosystem to support institutional growth, human capital, and academia–industry cooperation in technology development.

Three-part structure of this book

Part 1: **The clean hydrogen economy and Saudi Arabia: domestic developments (Chapters 2–6)** examines hydrogen developments along the value chain,

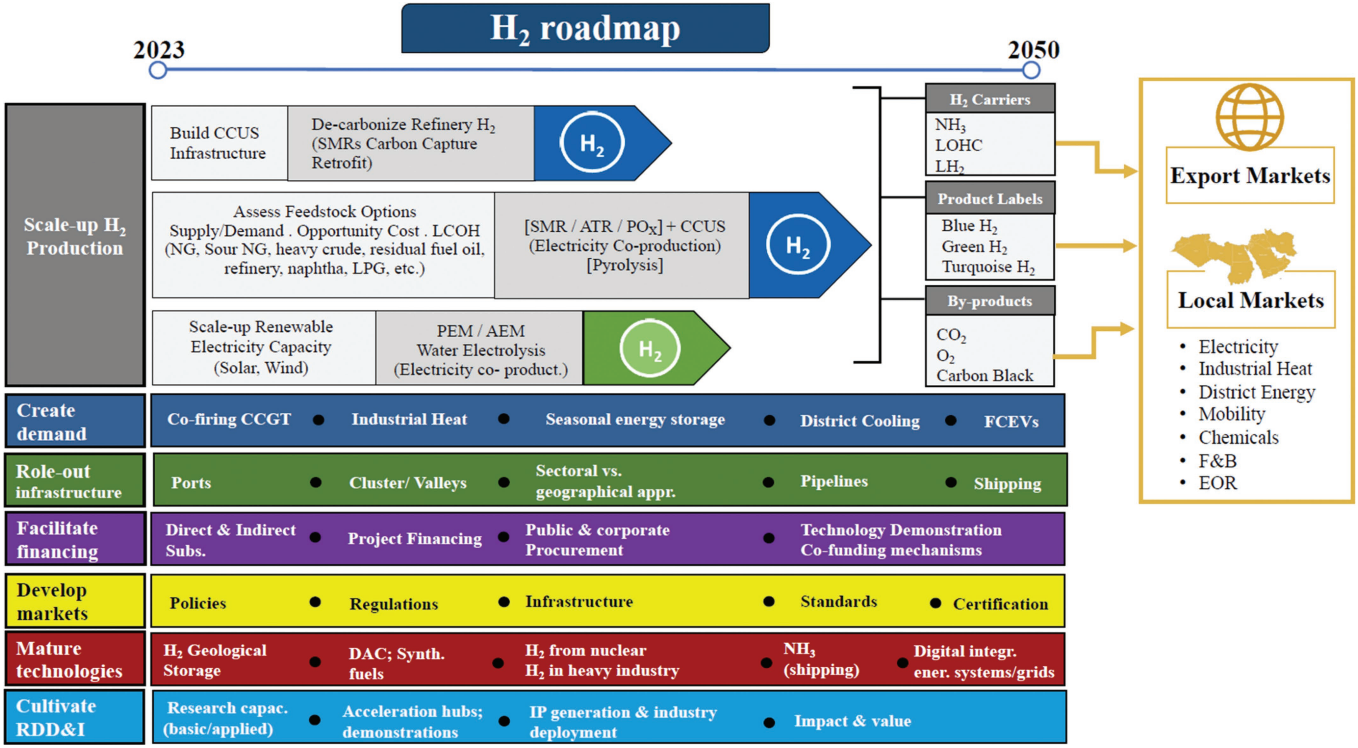

FIGURE 1.8 Clean hydrogen economy roadmap (2023–2050).

LEGEND: CCUS: Carbon Capture, Utilization, and Storage; SMR: Steam Methane Reforming; ATR: Autothermal Reforming; PO_x: Partial Oxidation; PEM: Proton Exchange Membrane; AEM: Anion Exchange Membrane; LCOH: Levelized Cost of Hydrogen; LOHC: Liquid Organic Hydrogen Carrier; LH_2: Liquid Hydrogen; FCEVs: Fuel Cell Electric Vehicles; EOR: Enhanced Oil Recovery; F&B: Food & Beverage; CH_4: Methane; NH_3: Ammonia; CO_2: Carbon Dioxide; DAC: Direct Air Capture; NG: Natural Gas; LPG: Liquefied Petroleum Gas; CCGT: Combined Cycle Gas Turbine; H_2S: Hydrogen Sulfide.

Source: Wa'el Almazeedi and adapted by the authors. *) The items mentioned here are not necessarily placed in a chronological order but constitute all the aspects required for a hydrogen economy up to 2050.

(i.e., production, export, transport, application, and RDD&I) in industries and academic institutions.

Chapter 2 by Rami Shabaneh and Jan Frederik Braun introduces Saudi Arabia's journey toward clean hydrogen in terms of stakeholders, policies, governance, and socioeconomic developments. This chapter explains how renewables-based and low-carbon hydrogen are coming to play a crucial role in the country's decarbonization efforts. It describes the range of governance opportunities and challenges for the government and its various stakeholders. Opportunities include Saudi Arabia's low-carbon intensity petroleum value chain, world-class infrastructure, emerging hydrogen hubs along its coastline, and logistical and seasonal advantages. Challenges include the need to implement the regulatory framework required for clean hydrogen, including an inclusive certification scheme in line with the criteria set by import markets. Further obstacles are scaling up renewables and creating demand in the domestic market (post-2030). In line with the 1.5°C scenario, Chapter 2 indicates the massive role for hydrogen applications in the transport sector in the Kingdom, especially after 2035.

Having introduced domestic governance matters in Saudi Arabia, Chapters 3, 4, and 5 describe the three key players (or 'pillars') central to carrying out its hydrogen plans and achieving its ambitions: The Saudi Arabian Oil Company ('Aramco' or 'the Company'), the Saudi Arabian Basic Industries Company (SABIC), and NEOM.

Chapter 3 by Jim Krane and Jan Frederik Braun examines the role played by clean hydrogen in Aramco's economic diversification plans and its contribution to the domestic and international credibility of the Kingdom's climate actions. Aramco is both the dominant revenue provider for the Saudi government's fossil fuel-driven governance model and a vital participant in delivering the Kingdom's ambitions to reach net-zero greenhouse gas emissions by 2060. The Company has committed to reaching its own net-zero emissions within its Scope 1 and Scope 2 operations by 2050. To do so, it is heavily investing in researching and developing technologies and new business units to find climate-compliant uses and markets for hydrocarbon resources. Producing low-carbon hydrogen and products is a prominent feature of this future diversified portfolio. Aramco's hydrogen approach differs from that of other oil and gas supermajors that emphasize a narrow blue hydrogen-dominated path. While blue hydrogen is the chief focus, Aramco's plans also include investment in renewables and green hydrogen technologies that produce renewables-based hydrogen. The authors delve into hydrogen's role in Aramco's economic diversification plans, which have been described as a hedging strategy for coping with the potential decline in demand for unabated hydrocarbons. The main message from the chapter is that majors such as Aramco can strengthen their long-term resilience and reduce the risk of revenue disruption by expanding into clean hydrogen.

The petrochemical sector constitutes the second pillar of the Saudi economy. **Chapter 4** by Abdulaziz Aljodai, Pieter Smeets, Fahad Al Shehery, and Hicham Idriss introduces SABIC and discusses its institutional aims, relevance, and role in Saudi Arabia's hydrogen economy ambitions. SABIC is one of the largest petrochemical manufacturers globally, with operations spread over 50 countries. It views hydrogen's role primarily as a chemical feedstock but recognizes that it could serve as a decarbonizing fuel. Indeed, both blue and green hydrogen are set to play a crucial role in decarbonizing SABIC's carbon-intensive production processes, including methanol production, ammonia synthesis, and steelmaking. Establishing short- and long-term goals for electrification and hydrogen is important for SABIC's move toward decarbonization and sustainability. The chapter argues that SABIC could leverage its extensive experience in producing and supplying ammonia to its consumers. With its proven expertise in managing the CCUS value chain, SABIC stands to gain from exploiting its existing capabilities. The chapter also states that its extensive technical knowledge and focus on transitioning to a low-carbon future makes SABIC well placed to leverage its existing know-how. This could allow it to become a globally leading competitor in future hydrogen and ammonia markets and is a critical part of Aramco's plan to produce 11 million tons of blue ammonia by 2030.

NEOM, an economic region along the Red Sea coast in northwestern Saudi Arabia, is the central topic of **Chapter 5**. NEOM is destined to be a part of any future Saudi hydrogen ecosystem. Its abundant solar energy during the day and wind power at night provide the optimal weather conditions for the high-load production of low-cost green hydrogen. In this chapter, Frank Wouters describes NEOM's hydrogen strategy, including the rationale behind its green hydrogen production and potential use cases. He also discusses its research strategy and the development of the region's massive hydrogen facilities.

In **Chapter 6**, Saumitra Saxena, Bassam Dally, Kevin Cullen, and William L. Roberts identify future technologies that are necessary for scaling up and implementing the hydrogen economy. The chapter discusses the need to build an RDD&I ecosystem and proposes a pragmatic approach to applying academic research to industrial deployment, which can strengthen Saudi Arabia's goal of economic diversification. The chapter also conveys the steps needed for policymakers and research funders seeking to translate university research into public benefit more efficiently and effectively.

Part 2: The clean hydrogen economy and Saudi Arabia: international opportunities and challenges (Chapters 7–14) examines developments in prominent hydrogen-importing and -exporting countries and regions relevant to the Kingdom in terms of their economics and policies, geopolitics, and technologies.

Chapter 7 by Wa'el Almazeedi explores in-depth hydrogen developments across the Middle East and North Africa (MENA) region. It argues that Egypt, Morocco, Oman, Saudi Arabia, and the UAE have taken the lead in responding to the hydrogen opportunity. All these countries have started renewable and low-carbon hydrogen and ammonia projects, developed hydrogen strategies and roadmaps, and entered into collaborative agreements with industrialized countries. Simultaneously, the chapter states that these MENA countries face numerous mindset, industry, regulatory, and institutional challenges that could hinder them from capitalizing on this opportunity. This is especially so in the context of the narrow window of opportunity for CCUS-enabled hydrogen. A key challenge here is whether MENA energy suppliers can capture a meaningful share of the global energy market, as the energy transition compels countries, companies, and soon individuals globally to reduce their carbon emissions to net zero by 2050. In response, the chapter formulates a range of actions that will allow MENA countries to overcome these challenges.

Chapter 8 by Jan Frederik Braun, Ad van Wijk, and Kirsten Westphal analyzes the ongoing hydrogen developments in the member states of the European Union and the states outside this treaty-based organization. The overarching focus of this chapter is on current policy and regulatory developments, which have been turbocharged by the Russia/Ukraine conflict and Europe's rapidly developing export relations with fossil fuel exporters. Gulf players such as Saudi Arabia are long-standing energy partners of Europe. They have the capacity and know-how to produce low-carbon hydrogen and ammonia as well as the additional geopolitical and climate incentive to position themselves as reliable providers of clean energy for Europe. The problem is that European policymakers and industries have yet to formulate a coherent hydrogen import strategy. Moreover, Europe largely focuses on removing carbon emissions altogether in the medium-to-long term. Saudi Arabia's CCE approach focuses on commodifying carbon emissions. In other words, it aims to reframe the discourse on CO_2 from being viewed solely as a negative externality toward understanding the value that can be extracted from it. These different sustainability approaches and their end goals need to be reconciled in a collaborative 'modus operandi' policy approach.

Chapter 9 by Tianduo Peng, Xun Xu, Lining Wang, and Jiaquan Dai reviews the strategic, production, application, and research aspects of hydrogen development in China, which is now Saudi Arabia's largest oil customer and trade partner. Hydrogen offers one of the key ways of achieving China's climate change mitigation targets, and it has recently been at the forefront of China's public policy discussions. Significant resources have been invested to research its associated technologies, showcase its potential for commercial applications, and develop its market. With China's recent commitment to reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060, hydrogen has been gaining even greater policy and market momentum. The chapter also explores the potential for mutually beneficial collaborations between China and Saudi Arabia in the new 'hydrogen era.'

Chapter 10 by Naomi Boness and Gireesh Shrimali discusses hydrogen developments in the United States and considers the current policy and activities of the federal government. Specifically, this is related to setting national targets and providing funding to promote technology innovation and infrastructure scaling, including the landmark Inflation Reduction Act. The chapter also explores the deployment of hydrogen technologies at the state level, where policies, industries, and state-specific goals are influencing the scale and speed of hydrogen adoption. It examines California in detail because this state is the most advanced in developing decarbonization targets and associated policies. This has resulted in the commercial development and application of hydrogen in the transportation sector in California. This chapter finally explores the status of commercial activities and projects across the United States and compares its evolving hydrogen landscape with recent developments in Saudi Arabia.

Chapter 11 by Bart Kolodziejczyk explores the role of hydrogen in Australia's decarbonization strategy and discusses future export opportunities. With its vast renewable energy resources, long history of exporting commodities, and strong government support, Australia is emerging as a forerunner of hydrogen production and export globally. A range of industrial, technical, commercial, and entrepreneurial ecosystems are helping the country become one of the largest hydrogen production and export hubs globally. The scale of its projects, excellent domestic conditions for producing renewable energy on an industrial scale, and potential and vast offtake markets could make Australia a major competitor to Saudi Arabia in hydrogen exports. However, the chapter argues that numerous similarities and synergies can be developed in a joint Saudi–Australian effort to serve their common benefits.

Chapter 12 by Yoshiaki Shibata, Victor Nian, Amit Bhandari, and Jitendra Roychoudhury describes the role of hydrogen in decarbonization, industrial development, and energy security across India, Japan (Saudi Arabia's second and third largest export markets, respectively) and the Association of Southeast Asian Nations (ASEAN) countries. The chapter focuses on how Japan is leveraging its early start in developing a hydrogen ecosystem domestically. It also discusses how Japan is using its outreach within ASEAN and India to share technology, finance energy transition infrastructure, and help develop regional hydrogen markets. Developing hydrogen markets enables Japan, a resource-poor country, to push its hydrogen technology into these regions and secure supplies for its domestic market in return. Japan has focused on developing strategic, technical, and commercial relationships to help ensure its energy security. For the Kingdom, the advancement of regional hydrogen markets in ASEAN and India could allow it forge new collaborations and develop new business models. For ASEAN and India, hydrogen represents an opportunity to decarbonize their heavily fossil fuel-dependent sectors. However, they face the challenges of developing a domestic hydrogen market and participating in export markets. Hence, collaboration and cooperation on establishing hydrogen supply chains and developing applications would benefit Saudi Arabia, Japan, India, and ASEAN countries. The development of pilots and deepening of technical and commercial partnerships among these countries point toward progress in meeting net-zero targets.

Chapter 13 by Jinsok Sung and Zlata Sergeeva explores the role of hydrogen in South Korea, a major market in Asia with high demand for hydrogen. Because South Korea has limited possibilities for producing clean hydrogen at home, it is set to become a large-scale importer of hydrogen. The central message is that South Korea needs to seek international cooperation to secure a stable supply of low-carbon hydrogen and solve the technical challenges throughout the hydrogen value chain. International cooperation is required to guarantee a sufficient hydrogen supply and create the required end-use markets for hydrogen vehicles and fuel-cell products. Saudi Arabia and South Korea have a long history of cooperation and establishing partnerships in various economic sectors, including in multiple large-scale energy and construction projects. The authors state that South Korea and Saudi Arabia therefore have vast potential for collaborating along the hydrogen value chain. Recent steps between the two countries show that their relations are now developing into a strategic partnership. Saudi Arabia is increasingly playing an essential role in providing South Korea's energy security.

Chapter 14 by Yuri Melnikov delves into the strategic hydrogen opportunities in Russia (before the military conflict in Ukraine). The main message of this chapter is that hydrogen development is likely to be determined by an export focus and a technological strategic orientation than by demand in the domestic market. The lack of a domestic market in Russia will become a serious obstacle to achieving its ambitious export targets and developing know-how. Russian export-oriented hydrogen projects depend on the (still) unforeseen external demand for hydrogen in the future and (possibly) highly competitive global market. The chapter therefore claims that Russian hydrogen technologies will not be competitive internationally without any significant domestic hydrogen demand. Demand for domestic low-carbon hydrogen can only increase significantly by adopting more ambitious decarbonization policies. This seems unlikely in the foreseeable future. In the meantime, domestic demand can be stimulated by tightening transport emission standards, setting targets for public transport, phasing in hydrogen content in gas distribution networks, and offering tax incentives and subsidies.

Part 3: The clean hydrogen economy and Saudi Arabia: hydrogen technologies (Chapters 15–27) provides an in-depth analysis of the domestic and overseas development of hydrogen technologies with relevance to Saudi Arabia's ambitions. Experts from research and industry examine the state-of-the-art of critical technologies for Saudi Arabia's hydrogen value chain. These contributions also identify R&D gaps and devise roadmaps for the commercial-scale penetration of hydrogen into Saudi Arabia's economy. The findings serve as a practical guide for policymakers preparing long-term strategies and academic and research institutions targeting funding in selected research areas and building an enabling world-class infrastructure.

Chapter 15 by Saumitra Saxena and William L. Roberts reviews the state-of-the-art of climate change and air pollution research and considers whether clean hydrogen can play an indispensable role in achieving climate goals both globally and regionally. The authors explain possible pitfalls and their overall argument is that holistic climate policies must include air pollution mitigation and consider the potential environmental impact of a large-scale hydrogen economy.

Chapter 16 by Alexander John Cruz from Baker Hughes provides an overview of the latest technical developments throughout the hydrogen value chain, focusing on transport, storage, applications, and digital transformation. The engineering challenges for developing advanced materials and sensors as well as for the cost-effective integration of legacy and newly built systems are highlighted.

Chapter 17 by Michelle Schoonover, Mustafa Alkhabbaz, and Mark D'Agostini from Air Products discusses the shift from the traditional steam methane reforming-based gray hydrogen production to lower-carbon blue and renewables-based green hydrogen production. The chapter describes the technical milestones for producing net-zero blue hydrogen using Air Products' autothermal reforming at its Hydrogen Energy Complex in Alberta, carbon capture and storage at its Port Arthur plant, and green hydrogen/ammonia project at NEOM.

Chapter 18 by Erika Niino-Esser, Malcolm Cook, and Ralph Kleinschmidt, of thyssenkrupp Uhde discusses developing gigawatt-scale electrolysis as well as technological innovation that combines desalination with offshore wind energy to support flexible desalination production capacity for green hydrogen. The latest research on seawater electrolysis and commercial developments in direct reduced iron for greening the steel industry is also elucidated.

In **Chapter 19**, Deoras Prabhudharwadkar, William L. Roberts, Robert Dibble, and Larry Baxter elucidate the pioneering cryogenic carbon capture technology that allows cutting CO_2 and air-polluting emissions simultaneously. This technology also has the potential for direct air capture at scale. The authors provide a plausible path to decarbonizing Saudi Arabia's power sector by merging two technologies: hydrogen in gas turbines and cryogenic carbon capture technology with steam methane reforming. Hussein Hoteit and Abdulkader Afifi (**Chapter 20**) then investigate the fundamental research enabling geological hydrogen storage in depleted gas reservoirs and salt caverns.

In **Chapter 21,** Shashank S. Nagaraj and S. Mani Sarathy describe the development in the crucial area of e-fuels produced from green hydrogen and carbon capture and storage. They also explore their role in energy storage and power-to-X to offset the intermittency of renewable energy.

In **Chapter 22,** Bassam Dally delineates the roadmap for hydrogen penetration and decarbonization in four key heavy industries: iron and steel, cement, aluminum, and phosphate. The author discusses the technology readiness levels of a spectrum of potentially game-changing technologies and identifies the research needed to reduce emissions from heavy industry in Saudi Arabia. Internal combustion engines running on hydrogen or ammonia are logical options to rapidly carry the energy transition forward given the hundred-plus years of know-how and infrastructure.

In **Chapter 23,** James Turner, Sebastian Verhelst, and Manuel Echeverri Marquez provide a concise exposition on the progress of research and argument for internal combustion engines burning hydrogen in heavy-duty transport and ammonia in marine shipping, two hard-to-abate sectors.

Saudi entities such as the King Abdullah City for Atomic and Renewable Energy (K.A. CARE) and the King Abdulaziz City for Science and Technology (KACST) are engaged in wide-ranging applied research in strategically crucial areas for the country. KACST pioneered the development of solar-powered hydrogen production and utilization with the German-Saudi Arabian HYSOLAR program in 1986. In **Chapter 24,** KACST's Naif Alqahtani and colleagues summarize research on potentially disruptive technologies, including hydrogen from photochemical water splitting, plasma reforming, solid-oxide fuel cells, and the microwave-assisted conversion of plastics to hydrogen.

K.A. CARE's Sharaf Al Sharif, Abdulrahem Al Judaibi, and Saleh Al Harbi **(Chapter 25)** examine the extent to which nuclear energy can play a pivotal role in the hydrogen economy in Saudi Arabia. The current technology readiness levels and research needs of critical technologies such as high-temperature water electrolysis and advanced nuclear reactors are discussed.

Chapter 26 by Omar Behar, Saumitra Saxena, Deoras Prabhudharwadkar, Bassam Dally, and William L. Roberts provides a techno-economic analysis of producing, transporting, and cracking green ammonia; it suggests solar-based ammonia cracking to reduce energy penalties.

Chapter 27 by Friedrich Alt and Christopher M. Fellows discusses the water requirements for producing green hydrogen in Saudi Arabia. The chapter provides a unique perspective on water desalination technologies for electrolysis, their respective carbon footprints, and the need for the progressive implementation of renewables. These chapters provide industrial case studies of the technology readiness levels of emerging technologies, commercial-scale implementation of mature technologies, and R&D needs for further advancement.

Together, these chapters offer a concise list of promising hydrogen technologies and plausible roadmaps best suited to achieve Saudi Arabia's climate goals, economic objectives, and long-term environmental, social, and governance priorities.

The **Conclusion** summarizes the key points made in this book and draws key lessons for the hydrogen economy and Saudi Arabia. In particular, it reflects on the future hydrogen pathway for the Kingdom according to the pillars of the hydrogen roadmap (Figure 1.8).

Note

1 The technical components of a certification scheme are typically embedded in a standard, which is an agreed methodology for conducting a process.

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PART I

The clean hydrogen economy and Saudi Arabia

Domestic developments

2

SAUDI ARABIA'S CLEAN HYDROGEN JOURNEY

Past, present, and future

Rami Shabaneh and Jan Frederik Braun

Introduction

For the past 75 years, Saudi Arabia has been at the helm of global oil markets and a key and reliable supplier of energy. As the largest producer in Organization of the Petroleum Exporting Countries (OPEC), with the most significant spare oil capacity, it plays an influential role in meeting market supply imbalances and smoothing price volatility (Pierru, Smith and Zamrik 2018). Domestically, despite implementing new streams of non-oil revenues, oil exports still accounted for a large percentage of government revenues in 2019, approximately 67.5% (Fattouh 2021). Oil and gas also comprise a significant share of the local primary energy mix, with heavy incentives skewed toward their usage in the transport sector, electric power, water desalination, and industrial applications. As economies shift to cleaner and more sustainable sources of energy to meet their climate targets, the Kingdom's product portfolio must maintain stability in its balance of payments, generate employment, and continue its economic growth in a sustainable manner.

Clean hydrogen and its derivatives are a golden opportunity for the Kingdom in several ways. First, clean hydrogen constitutes a critical energy carrier that allows for the domestic decarbonization of hard-to-electrify sectors. Second, the country benefits from its natural resources, existing infrastructure, low-cost renewable electricity, geographic location for export routes, and availability of non-arable land. Hence, hydrogen provides Saudi Arabia with an opportunity to enhance its product offerings to maintain its position as a low-cost and low-carbon energy provider. Third, hydrogen can also rapidly scale up the deployment of carbon capture, utilization, and storage (CCUS), a key suite of technologies to decarbonize its oil and gas sector. Fourth, adding hydrogen to its manufacturing and export portfolio could diversify the country's economy, create jobs, and expand the use of its existing infrastructure, elements enshrined in Saudi Vision 2030.[1]

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In October 2021, HRH Prince Abdulaziz bin Salman, Saudi Arabia's Minister of Energy, announced that the Kingdom is targeting the production of 4 million metric tons per annum (mtpa) of clean hydrogen by 2030. The ambitious announcement came during the first Saudi Green Initiative forum inaugurated by HRH Crown Prince Mohammed bin Salman. The Saudi Green Initiative aims to provide a platform for enhancing environmental protection and tackling climate change. During this forum, the Crown Prince announced Saudi Arabia's net-zero emissions target by 2060. A short-term emissions reduction target was also set to cut greenhouse gas (GHG) emissions by 278 million tons of CO_2 equivalent by 2030 (compared with the base year of 2019). This was immediately reflected in the updated Nationally Determined Contribution (NDC) for the United Nations Framework Convention on Climate Change (Kingdom of Saudi Arabia 2021a). Both hydrogen and CCUS will play crucial roles in achieving these targets, and plans are underway to develop these technologies.

The successful implementation of this strategy requires, among other actions, continuous evolution in policies, investment in low-carbon technologies, and support toward human capital. It also demands a complete innovation ecosystem to capture and increase domestic value creation across the hydrogen and CCUS value chain. This value chain will look vastly different from that of fossil fuel-based energy commodities. This is because unlike oil and gas, hydrogen is a conversion, and not an extraction, business and can be produced virtually anywhere. Further, it complements electricity in the energy transition and value creation along the supply chain will be created closer to end users. This chapter analyzes the past, present, and future of Saudi Arabia's hydrogen governance to assess its ability to seize existing opportunities and the need to tackle several key challenges and become a hydrogen 'superpower' in any future (and increasingly carbon-constrained) global hydrogen market.

Past: a short history of hydrogen manufacturing in Saudi Arabia

Where it all started

Saudi Arabia has a long history of hydrogen production and use. The uptake of hydrogen in the Kingdom can be traced back to the beginning of the country's industrial development during the 1970s. The Saudi Arabian Fertilizer Company (SAFCO, now called the SABIC Agri-Nutrients Company, part of the Saudi Basic Industries Corporation, SABIC) was the first petrochemical company created in the Kingdom in 1965. It built its first ammonia and urea plant, SAFCO 1, in 1970 in Dammam using natural gas (methane) as a feedstock to produce hydrogen.

Before the 1970s, heavy industry in Saudi Arabia was virtually non-existent. Most investments in the Kingdom were directed toward urban infrastructure, light manufacturing, and construction materials (Looney 1988). With no domestic market for natural gas, the country's non-associated gas reserves were underexploited, while a large volume of associated gas produced from oil fields flared. The Kingdom diverted its attention toward industrialization with a primary focus on the downstream activities of the oil and gas sector to diversify its economy, create employment, and provide greater economic independence. Natural gas was vital to Saudi Arabia's industrialization strategy. In 1975, the government directed Aramco (before nationalization) to design and build its Master Gas System (MGS), financed by the then Public Investment Fund, to collect and process associated gas to end gas flaring. The Royal Commission of Jubail and Yanbu, established in 1975, designed and developed the coastal cities of Jubail and Yanbu into industrial areas. SABIC was then created to establish complexes in these two cities that would use the natural gas feedstock supplied by the MGS to produce a range of chemicals and petrochemicals for plastics, fibers, and fertilizers (Albqami and Mathis 2012). When the first phase of the MGS was completed in 1982, it started to serve a series of industrial plants in Jubail. These plants included facilities to produce ammonia, methanol, and steel, all of which require hydrogen or synthesis gas (a mixture of mainly hydrogen and carbon monoxide) as a feedstock (Table 2.1). The MGS continued to expand as the development of associated and non-associated gas supplies increased. By 2020, the MGS could process up to 18.3

TABLE 2.1 Saudi Arabia's experience with hydrogen production and its derivatives since the 1970s

Project	*Production start date*	*Location*	*Hydrogen/ synthesis gas feedstock source*	*Product(s)*	*Initial annual capacity (thousands of tons)*
SAFCO 1 (retired)	1970	Dammam	Methane	Ammonia Urea	200 330
Saudi Iron & Steel Co. (Hadeed)	1983	Jubail	Natural gas	Steel	800
Saudi Methanol Company (Ar-Razi)	1983	Jubail	Methane	Methanol	600
Al-Jubail Fertilizer Company (Samad)	1983	Jubail	Methane	Ammonia Urea	300 600
National Methanol Company (Ibn Sina)	1984	Jubail	Methane	Methanol	700

Source: SABIC Annual Report 1985.

Note: The capacity of some of these plants has expanded since the start date.

billion cubic feet of raw gas per day using a pipeline network that could transport dry gas and associated liquids to end users nationally (Saudi Aramco 2022a).

Hydrogen production in Saudi Arabia is estimated to be 2.3 million tons annually, or over 3% of global production.[2] It is primarily used to produce ammonia and methanol (both 41%) as well as refining (18%). In 2020, Saudi Arabia was the largest exporter of ammonia and methanol, averaging 5.2 and 4.5 million tons, respectively (WITS 2021a, 2021b). The Kingdom's world-class infrastructure and ports for handling ammonia and methanol exports will become a key feature in enabling the trade of clean hydrogen (and its derivatives) going forward.

HYSOLAR: experimenting with green hydrogen

The Kingdom has previously experimented with green hydrogen production. In 1986, Saudi Arabia signed a bilateral agreement with Germany to cooperate in a long-term program called HYSOLAR. HYSOLAR's main objective was to research, develop, and demonstrate hydrogen production from solar resources as well as the utilization of hydrogen as an energy carrier (Steeb, Seeger, and Aba Oud 1994). The program lasted 10 years (1986–1995) and was jointly managed by King Abdulaziz City for Science and Technology[3] and the German Aerospace Research Institute. Several other institutions, including the King Fahd University of Petroleum and Minerals, King Abdulaziz University, King Saud University, and the University of Stuttgart, also participated. As shown in Figure 2.1, three photovoltaic-electrolysis hydrogen production demonstration and testing plants

FIGURE 2.1 The three solar-hydrogen production facilities manufactured and operated as part of the German–Saudi Arabian HYSOLAR program, 1986–1995. Left: 350/500 kW solar-hydrogen production demonstration plant in Riyadh, Saudi Arabia (operated 1993–2000). Center: 10-kW-solar-hydrogen R&D facility in Stuttgart, Germany (operated 1987–2004). Right: 3-kW-solar-hydrogen test facility in Jeddah, Saudi Arabia (operated 1989–1995).

Source: Andreas Brinner, private photos provided to authors.

were constructed and operated under the program. Laboratories to test the utilization of hydrogen in hydrogen engines, catalytic combustion, and fuel cells were also established (Steeb, Seeger and Aba Oud 1994).

Despite the low solar-to-hydrogen conversion at the time, this cooperation created knowledge in both countries, with the scientists involved in the program publishing HYSOLAR results in 224 publicly available publications (Brinner and Steeb 2002). HYSOLAR motivated the development of comparable programs with similar setups in several countries, including the United States, Egypt, the United Arab Emirates, and Japan (Brinner and Steeb 2002).

Present: from gray to clean hydrogen

Saudi Arabia intends to leverage its 'molecule-based' experience and existing infrastructure to expand its hydrogen production capability, as the future market for hydrogen as an energy carrier is expected to grow. For oil and gas producers such as Saudi Arabia, investment in low-carbon hydrogen production and demand may prove to be the most cost-effective response to the energy transition. The Kingdom has the lowest renewable electricity costs globally and is home to large non-arable land areas suitable for renewable projects (Bellini 2021). Its vast hydrocarbon reserves and significant geologic storage capabilities for CO_2 sequestration will allow it to become a leader in blue hydrogen production. Much of the world has experienced several gas price crises, most recently in 2022, which have made blue hydrogen unattractive in the short term. By contrast, Saudi Arabia neither imports nor exports natural gas, meaning that its price is unaffected by global markets. Moreover, gas prices are adjusted using a government-sponsored price adjustment mechanism. Therefore, the Kingdom has announced plans to become a powerhouse producer of clean hydrogen from both renewable and natural gas for export and domestic use.

Analysis by the King Abdullah Petroleum Studies & Research Center (KAPSARC) shows that Saudi Arabia's green and blue hydrogen production costs are already competitive compared with those of other regions. At the current domestic price of gas ($1.25/million British thermal units), the production cost of blue hydrogen is estimated to be $1.34/kg (Hasan and Shabaneh 2022). This is almost 50% higher than the cost of gray hydrogen production. Green hydrogen, on the contrary, is slightly higher, at $2.16/kg, using the average of recent renewable energy auctions. However, the rate of the cost decline of green hydrogen—owing to the falling rates of renewable energy and electrolyzer costs—is faster than that of blue hydrogen and could reach parity with blue hydrogen by 2030 (Figure 2.2).

The Kingdom is targeting the production of 4 mtpa of clean hydrogen by 2030. In its first Sustainability Report, Aramco shed light on its blue hydrogen activities as part of its plan to reach its scope 1 and 2 carbon neutrality targets by 2050.[4] In the report, the company announced a production target of 11 mtpa for blue ammonia by 2030 (Saudi Aramco 2022b). This volume of ammonia would require

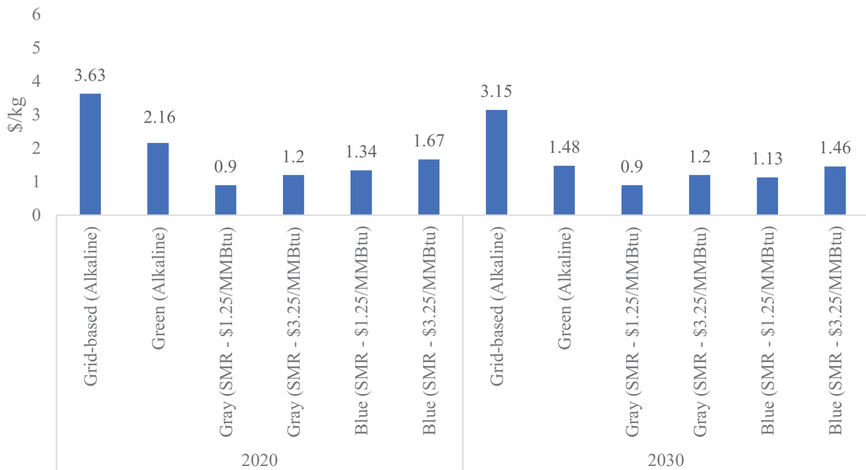

FIGURE 2.2 Production costs of blue and green hydrogen in Saudi Arabia, 2020–2030.

Source: (Hasan and Shabaneh 2022). SMR – Steam Methane Reforming; MMBtu – Million British Thermal Units.

approximately 2 mtpa of blue hydrogen. A large proportion of the natural gas to be used to produce blue hydrogen will be sourced from the Jafurah Basin, an unconventional non-associated gas field estimated to hold 200 trillion cubic feet of gas. Saudi Aramco has been developing Jafurah for some time to meet Saudi Arabia's domestic demand for natural gas and displace liquid fuels from its power plants (Fattouh and Shabaneh 2019). The development of the field is estimated to cost more than $100 billion and is expected to produce 2 billion cubic feet per day of sales gas (methane) by 2030 in addition to natural gas, liquids, and condensates (Saudi Aramco 2021a). Originally, gas was slated for export in the form of liquefied natural gas; however, the strategy has changed to focus on blue hydrogen exports instead (Samaha 2021).

Aramco is aware that for its blue hydrogen to be accepted as truly low carbon, not only should CO_2 emissions be mitigated but so must methane emissions from the wellhead to the site of hydrogen production. The good news is that Aramco has a head-start. According to the International Energy Agency (IEA) Methane Tracker, energy-related methane emissions in Saudi Arabia were estimated to be 2,820,000 tons in 2021 (IEA 2022). Hence, with natural gas production averaging 9.2 billion cubic feet per day for the same year, the methane intensity (methane emissions per unit of gas production) is approximately 0.04%,[5] one of the lowest globally (IEA 2022; Saudi Aramco 2022a).

NEOM (see Chapter 5), on the northwestern coast of Saudi Arabia, has laid the foundation for the country's commercial green hydrogen development and is scheduled to be part of any future Saudi hydrogen 'ecosystem.' NEOM is aiming to become a hydrogen hub that can provide the basis for the clean feedstock used to produce fertilizers, chemicals, and oil derivatives in collaboration with mega-players such as SABIC and Aramco. The NEOM Green Hydrogen Company (NGHC), one of the world's largest renewable hydrogen-to-ammonia facilities, marks the beginning of this ambition. The NGHC is a joint venture between Air Products, ACWA Power, and NEOM. Scheduled onstream in 2026, the facility will take advantage of the very high direct normal irradiance and wind speeds along the Red Sea in the northwest of the country. Equipped with 4 GW of renewables, which power the plant with the sun during the day and wind during the night, the electrolyzers at the NGHC will run at a high load factor. This will help produce an estimated output of green ammonia of 1.2 million tons per year. Air Products will be the exclusive off-taker of the ammonia. The company intends to transport this ammonia and dissociate it into hydrogen (and nitrogen) at delivery for use in the transportation sector (Air Products 2020).

To support its ambition in clean hydrogen development, Saudi Arabia has ramped up its international collaborations and strategic partnerships, inking memorandum of understanding (MoU) agreements with several potential and significant importing countries (Box 2.1).

BOX 2.1 OVERVIEW OF SAUDI ARABIA'S BUSINESS-TO-BUSINESS AND GOVERNMENT-TO-GOVERNMENT MoUs

Japan: Saudi Arabia's formal cooperation with Japan on clean energy dates back to 2016 when the Saudi Ministry of Energy, Industry, and Mineral Resources signed a memorandum of cooperation with Japan's Ministry of Economy, Trade and Industry (METI) to explore renewable and low-carbon energies. This eventually became part of greater cooperation between the two countries under the Saudi Vision 2030 framework formed in 2017. The first hydrogen-specific MoU with Japan was signed in 2019 between Aramco and the Institute of Energy Economics, Japan (IEEJ), the research arm of the METI (Saudi Aramco 2019). The MoU resulted in the 'first-of-a-kind 40-ton demonstration shipment' of blue ammonia from Saudi Arabia to Japan, providing a valuable test case for exploring future commercial viability and deployment.

Germany: Saudi Arabia's Ministry of Energy signed a government-to-government MoU with Germany's Ministry for Economic Affairs and Energy in early 2021 (Figure 2.3).

This MoU aims to promote bilateral cooperation in producing, processing, applying, and transporting '*sauberen*,' or clean hydrogen, and joint marketing projects by (BMWK 2021)

FIGURE 2.3 Signing of the Saudi–German MoU in Riyadh on March 21, 2021.

Source: Saudi Arabia Ministry of Energy 2021a.

- Involving the relevant stakeholders from research institutions and private and public sector entities to implement appropriate activities.
- Promoting mutual knowledge sharing and technology transfers to Saudi stakeholders and deploying German technologies to implement and localize new technologies for start-up projects in the Kingdom.
- Implementing concrete projects, including NEOM.
- Facilitating the development of a CO_2-neutral hydrogen sector in Germany.
- Establishing a Saudi–German innovation fund to promote clean hydrogen.

These efforts were followed up in 2022 with the first-ever bilateral Saudi–German hydrogen study that explored bilateral avenues of cooperation on production, trade, transport, storage, and applications. It found that Germany and Saudi Arabia possess the resources, infrastructure, and skills to produce cost-competitive hydrogen by cooperating across value chains. In addition, in areas such as storage, the study stated that there is 'an enormous need to invest in R&D capacity and technology transfer to Saudi Arabia' (Braun et al. 2022).

South Korea: This business-to-business MoU between Aramco and South Korea's Hyundai Heavy Industries Holdings (HHIH) was signed in early 2021. As with the Aramco–IEEJ MoU, Aramco's agreement with HHIH should facilitate the further exploration of R&D opportunities in the areas of blue hydrogen, including the production of blue hydrogen from liquefied petroleum gas, and utilizing hydrogen in refining and transport (Saudi Aramco 2021b). In 2022, a tripartite MoU was signed in the area of green hydrogen between Saudi Arabia's Public Investment Fund, Samsung C&T, and the Korean Steel Making Company, POSCO. This MoU aimed at the production and export of green hydrogen (SPA 2022a).

The United States: During President Biden's visit to Jeddah in July 2022, Saudi Arabia and the United States signed a partnership framework to advance clean energy, including the implementation of the circular carbon economy (CCE), CCUS, and clean hydrogen (Darweesh 2022). However, details of this agreement are currently unavailable.

Greece: As part of an official visit by HRH Crown Prince Mohammed bin Salman to Greece in July 2022, an MoU was signed between Saudi Arabia's Minister of Energy and Greece's Minister of Foreign Affairs, which included cooperation on clean hydrogen and its transfer to Europe (SPA 2022b). While the MoU does not detail export options to Greece, a pipeline option across the Mediterranean could be envisaged.

China: In August 2022, Saudi Aramco and Sinopec signed an MoU with a wide range of technical cooperation, including carbon capture and hydrogen (Saudi Aramco 2022c). Saudi Aramco and Sinopec already have joint-venture assets in refining and petrochemicals in both Saudi Arabia and China. However, this is the first time the two companies are collaborating on clean energy technologies. Sinopec, the largest producer of hydrogen in China, plans to source 60% of its hydrogen production from renewable energy by 2025 (Ylhe and Collins 2022).

Domestically, the Ministry of Energy has signed eight MoUs with several local entities to explore hydrogen use in transportation applications (hydrogen fuel-cell vehicles, buses, rail), the refueling infrastructure, and manufacturing sustainable jet fuels (Saudi Gazette 2022). The heavy focus on the domestic use of hydrogen for transport has been supported by the release of technical standards for hydrogen-powered vehicles by the Saudi Standards, Metrology and Quality Organization. The standards were approved in March 2022 along with standards for storage tanks and hydrogen discharge systems, including components designed for liquid and compressed hydrogen (Kenji 2022). In 2020, the transport sector was the third-largest contributor to CO_2 emissions (24%) in Saudi Arabia, following the industrial (28%) and energy (47.2%) sectors (Al Shehri et al. 2021). Thus, clean hydrogen can play a significant role in reducing emissions in the Kingdom.

Future: the CCE and hydrogen strategy

The implementation of the CCE framework is a key tool shaping Saudi Arabia's energy policy. The CCE concept was pioneered during Saudi Arabia's 2020 G20 presidency and is best described as an extension of the idea of a circular economy, where materials and waste can be managed through the 3Rs: reduce, reuse,

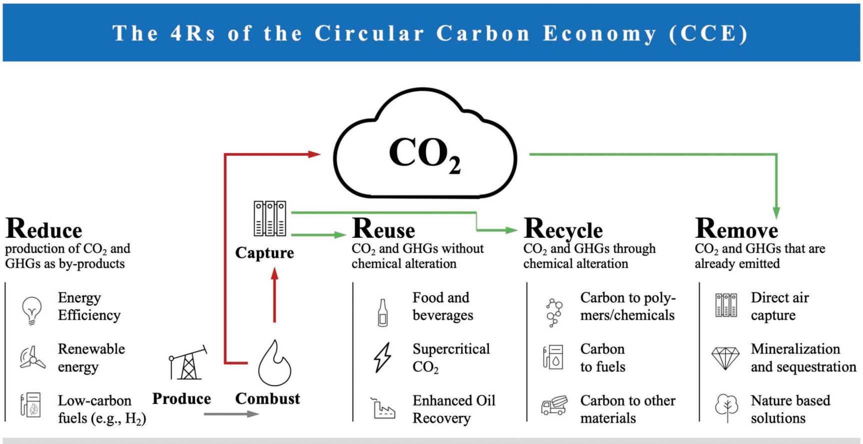

FIGURE 2.4 The 4Rs of the CCE.

Source: Al-Ghareeb (2022).

and recycle. The CCE focuses exclusively on carbon and energy flows. It represents a framework under which carbon emissions from all sectors are addressed through a closed loop in which emissions can be mitigated through the 3Rs as well as 'removed,' as Figure 2.4 shows. How much each of these 4Rs contributes in a jurisdiction depends on factors such as the cost and performance of the technology and resource availability as well as other national circumstances. This gives it a more pragmatic approach to tackle climate change (KAPSARC 2020). The energy ministers of the G20 endorsed the CCE concept, and the national CCE program was launched during a side event of the G20 summit in 2020 (SPA 2020).

The CCE approach requires enhanced international cooperation to standardize the measurement, reporting, verification, and certification of the emissions content of internationally traded products. The three-point action plan proposed in the G20 policy brief includes the following (Fattouh et al. 2021):

a Measuring the carbon content to consider product lifecycles from inception through energy intermediates to final processing.
b Reporting and verifying emissions in a uniform and transparent manner and according to Generally Accepted Accounting Principles for emissions.
c Certifying GHG content based on an internationally recognized methodology for relevant internationally traded products.

The Saudi government views hydrogen applications as a cross-cutting component of the CCE, as Figure 2.5 shows, especially as a critical enabler in decarbonizing hard-to-abate sectors (IEA 2020):

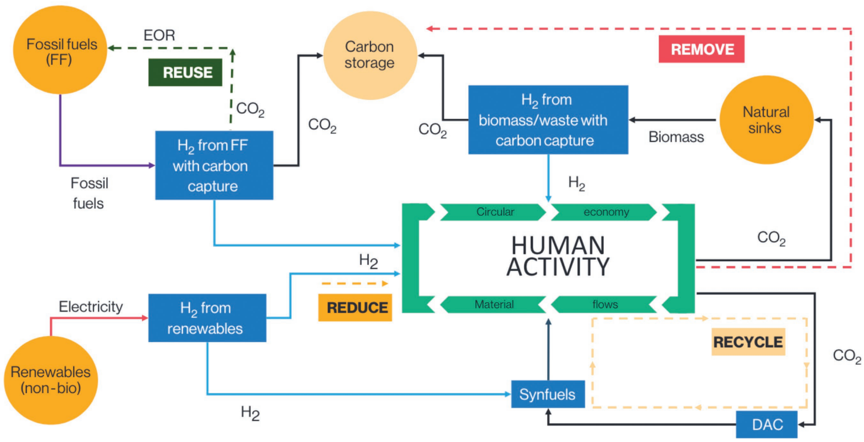

FIGURE 2.5 Hydrogen technologies under the CCE.

Source: IEA 2020.

- **Reduce:** The substitution of high-carbon fuels with clean hydrogen can reduce the carbon entering the system. Replacing the hydrogen produced by conventional routes in current uses, for example, by retrofitting CCUS with existing fossil-fuel-based hydrogen production plants, and expanding the use of clean hydrogen in new applications can reduce GHG emissions.
- **Recycle:** Hydrogen-derived synthetic hydrocarbons can directly replace conventional fossil fuels such as diesel and kerosene. These synthetic fuels are produced by combining carbon with hydrogen; using captured CO_2 would enable a route for carbon recycling.
- **Reuse:** CO_2 is captured during fossil fuel-based hydrogen production and reused in applications such as enhanced oil recovery.
- **Remove:** The production of hydrogen from biomass with carbon capture and storage removes CO_2 from the system and can result in negative CO_2 emissions.

Hydrogen is also featured in Saudi Arabia's updated first NDC under the United Nations Framework Convention on Climate Change (Kingdom of Saudi Arabia 2021a). This NDC aims to reduce, avoid, and remove 278 million tons of CO_2 equivalent annually by 2030 compared with the 2019 level. The core pillars of the Kingdom's sustainable economic diversification efforts are the production of both green and blue hydrogen, with climate mitigation co-benefits. The NDC also states that deploying and collaborating on technologies such as CCUS and clean hydrogen is crucial to reaching the Paris Agreement goals given their abatement potential (Kingdom of Saudi Arabia 2021a). Despite these efforts, however, a research group that tracks progress toward achieving the Paris Agreement has identified Saudi Arabia's NDC as highly insufficient due to weak and unclear policies and domestic targets inconsistent with the 1.5°C temperature goal (Climate Action Tracker 2021).

Regarding blue and green hydrogen production, the Saudi government will be instrumental in driving initial blue and green hydrogen production projects such as NGHC, infrastructure demands, and providing financial support for CCUS, for example. This is the same for all governments that wish to build local production capacity, whether for domestic consumption or export. The Saudi Arabian hydrogen strategy requires a range of targets, goals, and measures, which are necessary to incentivize investment in hydrogen production, transport, and application. Saudi Arabia's hydrogen opportunities also extend beyond its borders. Specifically, the country can participate in projects of common interest with other Gulf Cooperation Council (GCC) and neighboring countries in order to attain economies of scale, and human capital, and technical resources in a cost-efficient manner. Candidate projects include regional CCUS and hydrogen 'valleys' or 'hubs' that allow for scaling up production, cooperation, demand, and infrastructure across GCC nations and beyond (Figure 2.6) (Braun and Shabaneh 2021).

FIGURE 2.6 The regional hydrogen economy within and beyond the GCC countries: a conceptual illustration.

Source: Authors.

The Kingdom's national hydrogen strategy focuses on the production, export, and domestic use of hydrogen in transport and transport fuels, refining, chemicals, and direct reduced iron steel (Braun et al. 2022). This strategy aims to establish the following:

i The essential aspects of the green and blue hydrogen production process.
ii Domestic hydrogen demand use cases in the transportation industry (heavy- and light-duty vehicles).
iii The hydrogen used in products with export potential (synthetic fuels and steel).
iv Hydrogen exports to potential markets in Europe, Asia, and globally.

Domestically, the Saudi government is aiming to bridge the cost gap between fuel-cell vehicles and internal combustion engines and understand where the former might outperform battery electric vehicles. It is also discussing the adoption of long-haul, heavy-duty, and high commercial vehicles, including trucks, public buses, and airport taxis at the four largest airports of the Kingdom: Riyadh, Jeddah, Mecca, and Medina.

A longer-term focus beyond 2030 aims to build capacity through pilots and R&D as follows:

- Hydrogen-based green steel produced via the direct reduced iron process, including a pilot plant (commercialization expected after 2030).
- Synthetic fuels for aviation that combine hydrogen with CO_2 including R&D (commercialization expected after 2035).
- Ammonia and methanol as marine fuels to help meet International Maritime Organization regulations (commercialization expected after 2035).

To support the deployment of hydrogen across Saudi Arabia's value chain for domestic use and export, several enabling mechanisms are being considered:

- Support and enforcement mechanisms
- Demonstration, pilots, and R&D
- Standards and technical regulations
- Awareness and global partnership building across the value chain with major demand markets in Europe and East Asia (e.g., Germany, South Korea, and Japan).

Saudi Arabia's hydrogen governance: actors and institutions

Governance under the Kingdom's monarchial rule is characterized by continuity, as the government is not exposed to the pressure to tailor policy to short-term election cycles, and there is no legislature or veto-wielders who can block the ruler's directives (Krane 2022). These facts of Saudi governance allow long-term policymaking to respond to structural challenges such as climate change mitigation and setting the Kingdom on a new energy path, which includes hydrogen. At the core of Saudi Arabia's hydrogen governance is its extensive Integrated Energy Strategy framework. This framework includes hydrogen and CCUS as key pillars alongside four already existing pillars, namely oil; natural gas; refining and petrochemicals; and power, renewables, and nuclear energy (KAPSARC 2023). The framework aims to set goals, policies, strategic trends, and initiatives and measure performance to maximize the added value in the national economy while enhancing sustainability and energy efficiency.

The Ministry of Energy has a higher level of technical competency and international diplomatic experience than most other departments of the Saudi government. Owing to the role of energy, including oil and gas, in the Saudi economy, the governance of the country's energy and climate policies has evolved over time. The Ministry of Energy has led the process of formulating and following the execution of these policies.

According to Saudi Arabia's Basic Law of Governance, the Council of Ministers (or the Cabinet) has final authority for financial and administrative affairs, including the implementation of policies emanating from all ministries. In 2015, a royal decree restructured the Cabinet by forming two subcommittees to support policymaking in the Kingdom: the Council on Political and Security Affairs and the Council of Economic and Development Affairs. In 2018, the hydrocarbon governance structure was reorganized by enacting the hydrocarbon law and setting up the Supreme Committee for Hydrocarbon Affairs charged with hydrocarbon issues. In 2020, the Supreme Committee for Energy Mix Affairs for Electricity Production and Enabling the Renewable Energy Sector was set up to align policies and decision making on renewable energy, the optimum energy mix, and localization programs (Abdel-Baky and Garcia 2022). The Supreme Committee for Hydrocarbon Affairs later set up the Hydrocarbon Demand Sustainability Program to enhance hydrocarbon use while increasing environmental and economic efficiency (Kingdom of Saudi Arabia 2021b). This program focuses on finding ways to replace traditional materials with innovative ones derived from hydrocarbons based on research and innovation.

The integrated energy strategy framework spells out six strategic objectives including emissions management and local content, along with the required key enablers that are being developed through collaboration among public and private sector entities participating in the Kingdom's 'Energy Ecosystem' (KAPSARC 2023). Such entities include the Saudi Energy Efficiency Center, Water & Electricity Regulatory Authority, King Abdullah City for Atomic & Renewable Energy, KAPSARC, Saudi Aramco, and SABIC.

Saudi Arabia's hydrogen opportunities and challenges

Opportunity: low GHG-intensity value chain

Saudi Arabia is a leading oil producer, as it has one of the lowest carbon intensities in its petroleum value chain. Indeed, it ranks second among the 50 leading oil-producing countries on a wells-to-refinery gate basis, averaging 27 kg of CO_2 equivalent/barrel (Masnadi et al. 2018). Its low fugitive methane emission rates and low gas-flaring intensities support these figures. Saudi Arabia's flaring intensity averaged 0.6 cubic meters of gas per barrel in 2021, the lowest among oil- and gas-producing countries in the Middle East and much lower than major oil- and gas-producing countries such as Russia and the United States at 6.9 and 2.1 cubic meters of gas per barrel, respectively (GGFR 2022). Under the Oil & Gas Climate Initiative, Aramco has committed to take upstream methane emissions to near zero by 2030 as well as signed up to the World Bank's Zero Routine Flaring by 2030 initiative. Moreover, a methane leak detection and repair program has been rolled out within the company to minimize fugitive methane emissions. The company's methane intensity is one of the lowest in the industry globally, with an average of 0.05% in 2021 (Saudi Aramco 2022b). Having a low GHG emission intensity along the natural gas value chain will be crucial for Saudi Arabia's quest to become a global hydrogen player. This is particularly with regard to the blue hydrogen pathway, as emissions thresholds in most importing regions consider emissions starting from the well-head.

Aramco has also gained significant know-how in CCUS, especially since the Uthmaniyah demonstration CO_2/enhanced oil recovery plant came onstream in 2015. One of the largest globally, the plant can capture and sequester 800,000 tons of CO_2 per year, which is also used for permanent storage in saline aquifers (Al Khowaiter and Mufti 2021). In addition, SABIC has been operating 500,000 tons of CO_2 per year carbon capture and utilization plant at its affiliate United using proprietary technology to capture CO_2 for use in a range of industrial processes. SABIC's experience with CO_2 utilization could complement Saudi Aramco's CCUS capabilities, opening the spectrum of CO_2 use beyond storage and enhanced oil recovery (Al Khowaiter and Mufti 2021). In 2022, both Aramco and SABIC received the world's first independent certification by TÜV Rheinland for the production of blue hydrogen and ammonia, respectively (Saudi Aramco 2022d).

Opportunity: world-class infrastructure and emerging hydrogen hubs

The Kingdom has established a competitive presence in the emerging hydrogen market. This competitiveness is based on three main factors. The first is Saudi Aramco's long and proven track record of utilizing its oil and gas assets and infrastructure. The second is SABIC's leading chemical position and asset base. Finally, Saudi Arabia benefits from their combined expertise in large-scale CCUS operations. Jubail and Yanbu, where most hydrogen is produced, form the industrial heartland of the Kingdom. Managed by the Royal Commission of Jubail and Yanbu, an autonomous organization of the government, Jubail and Yanbu are home to some of the largest industrial complexes. Their facilities include chemical plants, refineries, seawater desalination plants, and utilities with adjacent ports (Braun and Shabaneh 2021). In January 2020, Air Liquide commissioned a 16-km hydrogen pipeline network connecting its 340,000 Nm^3/hour hydrogen production facility at the YASREF refinery to other nearby facilities, including refineries and other industrial companies (Sampson 2020). In Jubail, Air Products Qudra and the Royal Commission of Jubail and Yanbu plan to build a world-scale steam methane reformer capable of producing over 400,000 kg of hydrogen daily (McDonald 2020). They are also developing a comprehensive pipeline system to distribute industrial gases to refineries and industrial customers (McDonald 2020). This hydrogen infrastructure will make the Royal Commission of Jubail and Yanbu a growing and upcoming hydrogen hub. Further, carbon capture and storage plants will be retrofit to these facilities, especially in Jubail, which has ample CO_2 storage sites nearby and CO_2 utilization opportunities. This will provide a rapid pathway for decarbonizing existing assets. Similarly, green hydrogen projects in OXAGON, the industrial city in NEOM, could easily link the industrial facilities and ports in Yanbu.

Opportunity: logistical and seasonal advantage

Saudi Arabia has geographic and logistical advantages. First, it is located within easy shipping distances to large and growing clean energy markets. For example, the NEOM region on the northern tip of the Red Sea coast is well located next to the Suez Canal, which allows quick access to the hydrogen markets in Europe. Similarly, the port of Jubail on the Arabian Gulf is close to the developing hydrogen markets in East Asia (Figure 2.7).

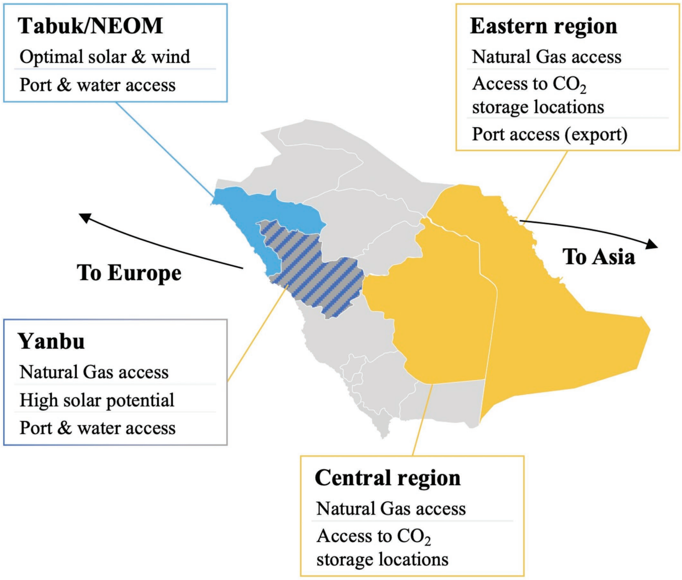

FIGURE 2.7 Saudi Arabia's advantages for exporting hydrogen.

Source: Al-Ghareeb 2022.

Another advantage is the counter-seasonal peak energy consumption profile in Saudi Arabia compared with energy importers in the northern hemisphere. Most energy demand in Saudi Arabia is during the summer, primarily for air conditioning. However, during the winter, when demand in Europe and Asia is high, especially for heating, renewable energy and natural gas resources can be used to meet export demand. In this way, the Kingdom can benefit from the premium in seasonal price differences.

Opportunity: parallel strategies for renewable and low-carbon hydrogen

A parallel focus on green and blue hydrogen can highlight the complementarity between these two hydrogen types, which can overcome significant infrastructure challenges. Figure 2.8a shows that the vast majority of blue hydrogen production, demand, and infrastructure is in the eastern and central provinces. By contrast, the area that holds the most promise for green hydrogen is the northwest of the Kingdom. However, this region shows little to no industrial-scale production, demand, and infrastructure requirements, which will need to be built from scratch, and rapidly. Instead of focusing exclusively on one of these production methods, balanced approach between renewable and low-carbon hydrogen production and demand allows for the built up of all aspects of the hydrogen value chain in the northwest and other parts of the country while reducing the burden on land use and resources.

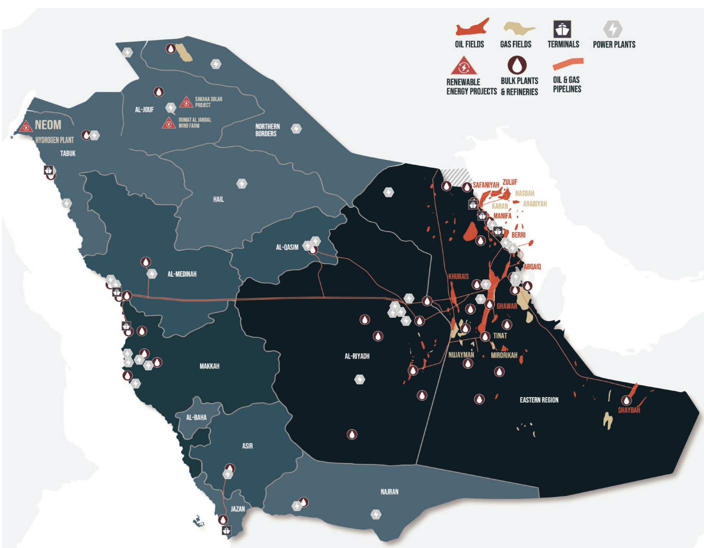

FIGURE 2.8A Saudi Arabia's energy map.

Source: KAPSARC.

An additional argument for adopting a balanced approach comes from the results of a prominent temporal-spatial high-resolution simulation of the optimal locations for power-to-X (PtX) production (including gaseous and liquid hydrogen) in Saudi Arabia. This analysis shows that most of the potential in Saudi Arabia is located along its coastal waters (Figure 2.8b).

This analysis ranks the optimal areas in the Kingdom using strict sustainability criteria related to the use of nature conservation and protected areas, level of water

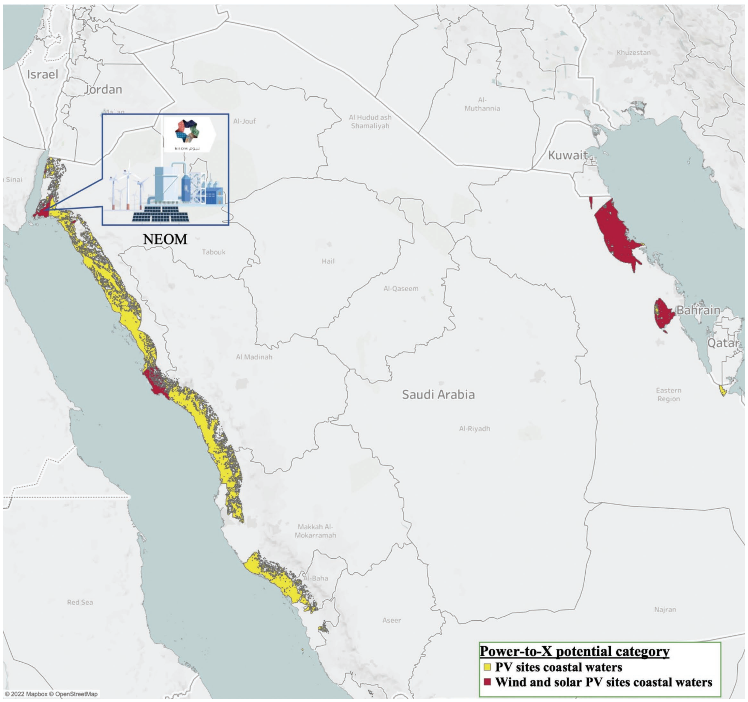

FIGURE 2.8B Suitable locations for power-to-X fuels in Saudi Arabia (up to 2050).

Source: Authors based on Fraunhofer 2022.

stress, and use of agricultural land and forest. Other criteria include the distance to ports and pipelines, distance to cities, and distance to coastlines (Pfennig et al. 2022). Based on these and other indicators, the analysis shows the optimal solar photovoltaic areas for hydrogen production throughout the Kingdom (including the NEOM region in the northwest) as well as suitable areas for solar and wind in the eastern region.

The sustainability criteria that underline the analysis of Figure 2.8b are important for the Kingdom's stakeholders to consider for a balanced approach toward its hydrogen production. Equally important is integrating this kind type of technical and economic analysis into its policy planning, which is underpinned by data with a high temporal and spatial resolution and state-of-the-art modeling. This will be essential for the government to effectively identify suitable locations for hydrogen production. These 'climate change-resilient' governance tools are required for the Kingdom to carry achieve out its net-zero-by-2060 ambitions and contribute to making sure that its hydrogen exports meet certain international standards and criteria.

Challenge: CO_2, low-carbon and renewable hydrogen and the regulatory framework

Many countries and regions have started adopting climate policies to accelerate low-carbon technologies. However, these efforts have not thus far accelerated meaningful regulatory policies for low-carbon technologies, particularly in hard-to-abate sectors. For example, in the sixty-eight carbon pricing initiatives worldwide (World Bank 2022), most carbon prices remain well below the \$40–80 per ton of CO_2 range needed to meet the Paris Agreement goal of 2°C (World Bank 2021). Without factoring in the cost of the externality caused by the increasing CO_2 emissions into the atmosphere, it would be challenging for clean hydrogen to compete with gray hydrogen.

Most countries lack the regulations, incentives, and emissions allowances to reduce CO_2 emissions. Exceptions are the EU Emissions Trading System, 45Q tax credit regime in the United States, US cap and trade markets, low-carbon fuel standard in California, and funding of demonstration projects by several member-state governments of the Organization for Economic Co-operation and Development (OECD). Hence, only a limited number of large-scale carbon capture facilities operate worldwide, and these are mainly in the United States, which can capture and store approximately 40 million tons of CO_2 every year (Global CCS Institute 2021).

Although Saudi Arabia intends to increase the share of low-carbon fuels in its energy mix, it still lacks enablers to reach its targets. The large-scale application of CCUS in Saudi Arabia is challenging because the technology is capital-intensive. In the absence of a framework that incentivizes investment in CCUS, cheaper blue hydrogen cannot be scaled up. Saudi Arabia lacks policies and incentives to drive CCUS projects, such as carbon prices, carbon taxes, regulatory requirements, grant support, tax credits, subsidies, contracts for differences, and loan guarantees. Although CCUS is an emissions mitigation option that contributes to economic diversification in the Kingdom's NDC, regulatory gaps are sizeable, as in other GCC countries. On the other hand, Saudi Arabia is aiming to capture 44 million tons of carbon annually by 2035 to achieve net-zero emissions by 2060 (Narayanan and Salloum 2022). Saudi Aramco took the first step in this endeavor at the end of 2022 when it joined with the Ministry of Energy to establish a carbon capture and storage hub in Jubail. This hub is aiming to have a storage capacity of 9 million tons of CO_2 per year by 2027. These efforts could provide a huge stimulus for the government to rapidly establish a suitable regulatory framework for CCUS.

Similar to the regulatory demands for blue hydrogen production and demand, the significant gaps in energy regulation must be bridged to create incentives for scaling up green hydrogen. The Ministry of Energy has created a hydrogen certification taskforce comprising both public and private entities in Saudi Arabia to institute a clean hydrogen certification framework that is inclusive and accepted by target markets in Asia and Europe (Al-Ghareeb 2022). Aligned with the Kingdom's clean hydrogen and Vision 2030 ambitions, the objectives of this framework are twofold. The first is to focus on the lifecycle emissions associated with the production of clean hydrogen. The second is to be inclusive of and directly mappable to the criteria set by the target markets' governing bodies and certification schemes.

Challenge: scaling up renewables

Renewable energy is the most significant component of green hydrogen. Thus, incentivizing renewable energy producers is critical for the development of a clean hydrogen industry in the Kingdom. Despite the potential of renewable resources in Saudi Arabia, the capacity of renewable power generation is dwarfed by the sheer size of fossil fuel-based generation capacity. There is approximately 443 MW of renewable energy capacity in Saudi Arabia, accounting for less than 1% of installed power generation capacity (IRENA 2022a). According to the Regulatory Indicators for Sustainable Energy, Saudi Arabia's legal framework for renewable energy is strong. However, the country scores average to weak in areas such as providing incentives and regulatory support and planning for the expansion of renewables (Table 2.2).[6]

The skewed incentives toward hydrocarbon use in a range of sectors, including utilities, have hindered the penetration of renewable energy and development of clean energy technology. As a result, Saudi Arabia's economy is highly carbon-intensive (Box 2.2).

TABLE 2.2 Policy and regulatory support for renewable energy in Saudi Arabia

Indicator	*Score*
Legal framework for renewable energy	**80**
Planning for renewable energy expansion	**48**
Incentives and regulatory support for renewable energy	**19**
Attributes of financial and regulatory incentives	**50**
Network connection and use	**20**
Counterparty risk	**58**
Carbon pricing and monitoring	**0**
Overall	**39**

Source: RISE (2021).

BOX 2.2 SAUDI ARABIA'S CO_2 EMISSIONS

Oil and gas dominate the country's primary energy consumption, with oil accounting for approximately 62% of the country's energy needs and gas 38% (Figure 2.9a).

Industry, which includes the mining, manufacturing, construction, and public works sectors, is the largest energy consumer in the Kingdom (35% in 2020), followed by the transport sector (27%), non-energy use in the petrochemical industry (21%), and households and services sector (16%).

CO_2 emissions increased significantly between 1990 and 2015 (i.e., 5% per year on average) (Enerdata 2022). Since 2017, the Kingdom has aimed for an annual decrease in CO_2 emissions from fuel combustion, characterized by a declining share of oil and an increasing share of gas (Figure 2.9b). This has been largely due to the energy price reforms in 2016 and 2018. On average, total CO_2 emissions fell by 1.24% between 2017 and 2021.

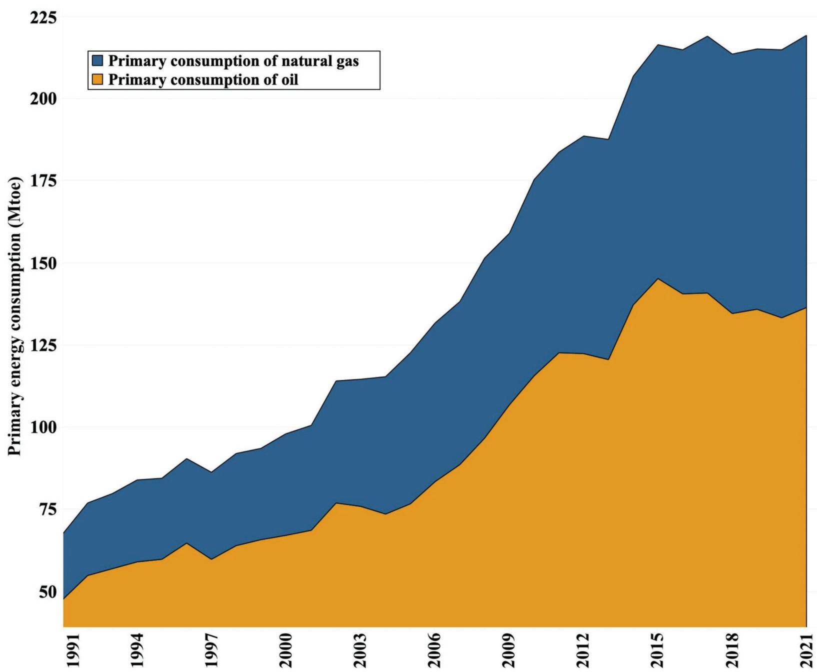

FIGURE 2.9A Saudi Arabia consumption trends by energy source (million tons of oil equivalent), 1990–2021.

Source: Authors based on Enerdata 2022.

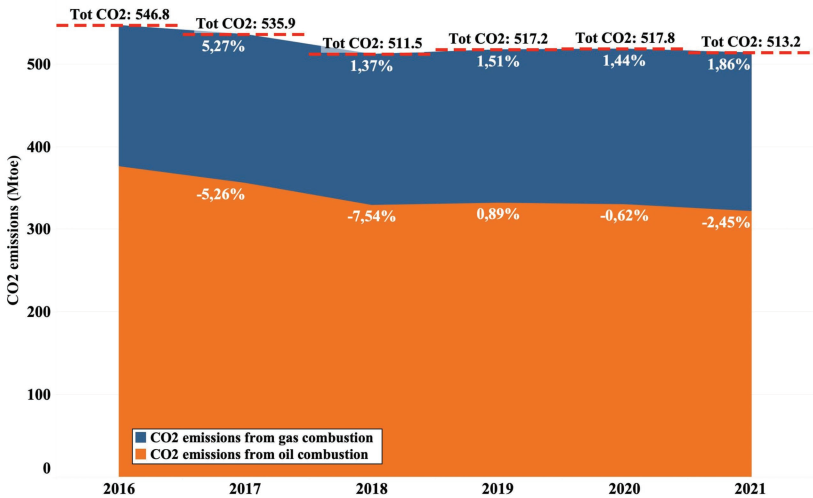

FIGURE 2.9B CO_2 emissions from fuel combustion, including year-on-year growth of oil and gas, 2016–2021.

Source: Authors based on Enerdata 2022.

The Kingdom plans to displace liquid fuels from its power mix, which accounted for 39% in 2021 (BP 2022). The goal is to achieve 50% of its power mix from renewable energy and the remaining 50% from gas by 2030 (Saudi Arabia Ministry of Energy 2021b). These ambitions will have to be matched with a rapid scale up of installed renewable capacity to decarbonize half the power sector by 2030 and create more dedicated renewable energy capacity for green hydrogen. Although several projects are planned, the installed capacity of renewables must increase spectacularly to match the Kingdom's ambitions in this area. For example, producing 1 million tons of green hydrogen would require over 10 GW of electrolyzer capacity, assuming a load factor of 50%. Powering this much electrolyzer capacity would require approximately 20 GW of renewable energy capacity.

Challenge: hydrogen market uncertainty, export vs. domestic, and carbon constraints

Having a solid presence in a nascent market such as low-carbon hydrogen would provide a competitive advantage for Saudi Arabia by securing exclusive contracts with essential buyers and service contractors. However, this comes with market risk. The cost of clean hydrogen production remains prohibitive, and the market is small and may take several years to grow. The demand trajectory for hydrogen ultimately depends on future decarbonization policies and the cost of alternative options.

Domestically, demand for hydrogen is only expected to significantly increase after 2030. This rise will depend on government policies and regulations creating a demand market for renewable and low-carbon hydrogen by partnering with end users across sectors and building the required infrastructure for usage and storage. As the Introduction of this book mentions, there remains a large amount of uncertainty about the size of the market for clean hydrogen. In any case, any focus on exports must be supplemented by focusing on creating local demand for hydrogen. This necessity is supported by the argument that the hydrogen value chain will be complementary to electricity and business models and demand- rather than supply-driven (Al-Mazeedi et al. 2021). Further, the creation of large-scale hydrogen demand will play an essential role in mitigation efforts in an increasingly carbon-constrained world.

Figure 2.10 shows hydrogen demand in Saudi Arabia under different scenarios until 2050. The EnerBase emission trajectory in the left-hand column visualizes a 'business-as-usual' situation in which limited efforts are made to mitigate GHG emissions. This would lead to an average global temperature increase of between 5°C and 6°C. EnerBlue in the middle column visualizes a scenario in which despite advanced GHG mitigation efforts, an average global temperature increase of between 3°C and 4°C still results. EnerGreen, on the right-hand side, constitutes a scenario in which ambitious GHG emission cuts are made in line with the Paris Agreement goal. This EnerGreen scenario resonates with the Kingdom's net zero by 2060 target and indicates a massive role for hydrogen applications in

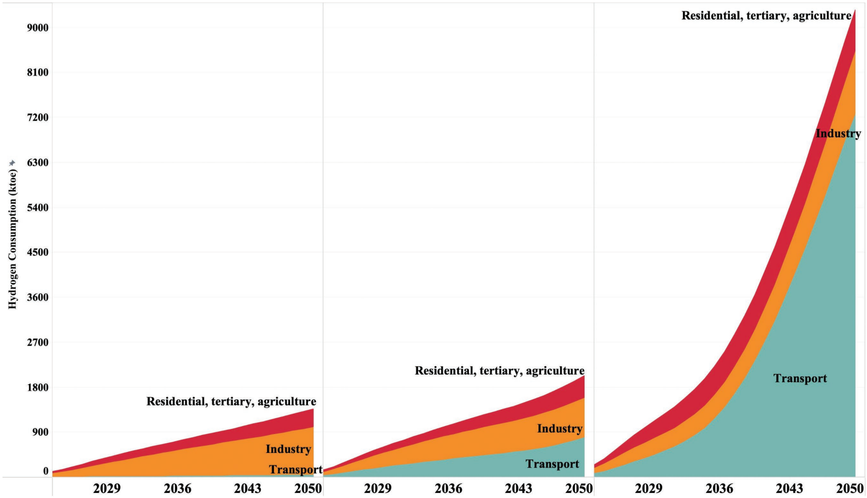

FIGURE 2.10 Final consumption of hydrogen by sector in Saudi Arabia, 2023–2050: Enerdata's EnerBase, EnerBlue, and EnerGreen scenarios.

Source: Authors based on EnerFuture 2022.

the transport sector. This is especially so after 2035, with the EnerGreen scenario implying a much more significant uptake of hydrogen in railway transport, aviation (e.g., using synthetic fuels), and maritime shipping (e.g., using low-carbon marine fuel such as ammonia and methanol). Under this scenario, low-cost hydrogen is also combined with CO_2 from the CCUS hubs in Jubail and Yanbu. The limited role of hydrogen in industry in the EnerGreen scenario can be explained by the strongly reduced need for refining capacity and the electrification of industrial processes. Overall, the large-scale development of a domestic hydrogen market is in line with the conclusions from IRENA. This body predicts that Saudi Arabia—in a 1.5°C scenario—will become the sixth largest demand market globally by 2050 after China, India, the United States, the Russian Federation, and Japan (IRENA 2022b).

Challenge: geopolitics

Similar to other countries, Saudi Arabia's hydrogen trade relations will be determined not only by technological and economic aspects but also by the geopolitics of energy transformation. This term implies not only a shift from one set of fuels to another but also involves a deeper transformation of the world's energy systems. Such a transformation will have major social, economic, and political implications that go well beyond the energy sector (Global Commission on the Geopolitics of Energy Transformation 2019). Geopolitical transformation factors that could affect the Kingdom's hydrogen ambitions include the (possible) regionalization of energy relations, shifts in inter-state relations, and the fact that the hydrogen business will be more competitive and less lucrative than oil and gas (IRENA 2022c).

Regionalizing energy relations is driven by the falling costs of renewable energy, with those for transport remaining high. This situation could create a stronger incentive for the Kingdom to vastly expand electricity transport and trading within and beyond GCC countries via transmission cables and cross-border infrastructure projects that link national energy systems and create regional demand. Hydrogen can be produced from many primary energy sources and is a manufactured product rather than a raw material or energy source. Hence, its trade flows are unlikely to lend themselves to geopolitical influence as oil and gas. Therefore, the fast-growing array of bilateral hydrogen deals will likely differ from the hydrocarbon-based energy relationships of the 20th century. Saudi Arabia is thus set to compete on a playing field that is radically different from that defined by the ability to produce, trade, and set production limits for fossil fuels in the global market. Finally, clean hydrogen does not generate returns comparable to the rents of oil and gas (IRENA 2022c). Hydrogen is a conversion, not an extraction, business and has the potential to be produced competitively in many places around the world. This limits the Kingdom's opportunity to capture economic rents akin to those generated by oil and gas. Therefore, in the long term, it may be more viable for Saudi Arabia to capture value further down the value chain by focusing on producing clean hydrogen-based end products such as steel, cement, and aluminum. Hydrogen-based end products can both decarbonize the domestic industry and create competitive advantages in carbon-constrained markets such as the EU.

Conclusion

The world is transitioning away from hydrocarbons. Therefore, clean hydrogen will become a means for Saudi Arabia to diversify its revenue streams away from unabated fossil fuels and monetize its oil and gas resources, create new jobs, and extend the life of its infrastructure and assets. As countries accelerate toward net-zero emissions at different rates, the Kingdom is likely to become a supplier of traditional and new sources of energy. Strategic advantages such as its low-cost and ample renewable resources, large land areas suitable for renewable projects and hydrogen facilities, low-cost natural gas, and vast existing oil and gas infrastructure make the Kingdom an ideal hydrogen producer and exporter. Therefore, its hydrogen strategy focuses on the production, export, and domestic use of clean hydrogen. This is also playing a cross-cutting role in its CCE approach and commitment to reach net-zero GHG emissions by 2060. Not only will hydrogen help decarbonize end uses domestically but its low-cost resource potential will also allow the Kingdom to become a major exporter of clean hydrogen, displacing the carbon-intensive fuels and feedstocks in other economies. Carbon management has become a pillar of the Kingdom’s energy strategy. This means all other operations in the energy ecosystem, including oil, gas, power, and petrochemicals, must ensure that carbon emissions are mitigated through the 4Rs (i.e., the mitigation options under the CCE). Hydrogen and CCUS, which are at the core of the CCE, present an opportunity for the Kingdom to maintain its position as a reliable, sustainable, and low-cost energy provider when energy security, economic growth, and sustainability become essential for meeting future energy needs.

The 4-million-ton-per-annum target of clean hydrogen by 2030 is ambitious but might need to be increased if the Kingdom wants to become the world’s leading hydrogen exporter (See Chapter 8). In any case, the current target can only be achieved in the short term with the right policies and regulatory frameworks in place. These are lagging behind, as is the required installed renewable capacity dedicated to renewable hydrogen production. Hence, the Kingdom will need to install large capacities in future years to meet its target of decarbonizing the power sector.

A shift to low-carbon fuels will likely reshape how economies use energy and, subsequently, how energy is traded. This will have implications for the Kingdom and its stakeholders, who will need to be agile and adaptable to increase their geopolitical leverage. Regarding hydrogen, Saudi Arabia is building on its existing energy partnerships and forging new ones. Collaboration with foreign governments and industries (domestic and international) is required to develop its export infrastructure, domestic demand, and R&D capabilities as well as introduce enablers to expedite hydrogen-related investment. In addition, government departments are collaborating closely to institute a clean hydrogen certification framework that is inclusive and in line with the criteria set by governing bodies and certification schemes in target markets.

Notes

1 Saudi Vision 2030 was unveiled in 2016 as a blueprint for the country's socioeconomic transformation. Diversifying the economy, creating jobs, and improving the standard of living for its citizens and residents are at the core of this Vision.
2 Figures are estimations and provided by KA CARE.
3 KACST led the development of the Kingdom's solar program and operated under a technical agreement with Germany.
4 Scope 1 emissions are defined as direct emissions sourced from an organization's owned assets and operations. Scope 2 are indirect emissions where the energy or heat used in the operation is not owned by the organization.
5 Assuming a methane density of 0.0192 kg per standard cubic feet. This is close to the 0.05% methane intensity stated by Aramco in its Sustainability Report.
6 RISE consists of a set of indicators to compare national policy and regulatory frameworks for sustainable energy across more than 130 countries worldwide. The score for the different indicators ranges between 0 and 100.

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3

SAUDI ARAMCO'S CLEAN HYDROGEN EFFORTS

Between economic diversification and effective climate action

Jim Krane and Jan Frederik Braun

Introduction

The Saudi Arabian Oil Company ('Aramco' or 'the Company') is both the dominant revenue provider for the Saudi government's fossil fuel-driven governance model and a vital driver of the Kingdom's ambitions to reach net-zero greenhouse gas (GHG) emissions by 2060. Aramco is the world's largest integrated energy and chemical company and a substantial contributor to direct and indirect atmospheric emissions. As such, its corporate strategy is crucial to the viability of the Kingdom's domestic and international approaches to climate change. Aramco is simultaneously the initial source of funds for Saudi Arabia's climate action, a key component of the Kingdom's climate brain trust tasked with devising appropriate measures, and a project manager responsible for building climate-related infrastructure. The Company's pivotal role in helping achieve the Kingdom's climate ambitions and continued economic growth is difficult to overstate.

Over the next few decades, Saudi Arabia could lose some of its geostrategic importance as the world's central banker of oil. This is because global oil demand may stabilize as oil substitutes make inroads in the transportation sector and efforts to price negative externalities related to carbon emissions increase (The World Bank 2022). As the importance of oil wanes, Aramco's contribution to decarbonizing the Kingdom could help the government demonstrate credibility in global climate action. Successful efforts in climate change mitigation could prolong Saudi Arabia's political and economic influence; this will grant policymakers the power to shape the energy transition in ways that could retain a greater long-term role for hydrocarbons—albeit in a cleaner form such as hydrogen.

Aramco's remit in Saudi Arabia could increasingly shift from overseeing a carbon-intensive industry to rendering the Kingdom an attractive destination

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for climate-compliant industrial production. This will be achieved by decarbonizing existing assets by electrifying processes and using renewable energy and energy efficiency, along with carbon capture, utilization, and storage (CCUS) technologies. Assisting the process is Saudi Arabia's copious renewable energy resources such as solar and wind, in addition to the close proximity of geological storage locations to the Kingdom's industrial zones and sites for future hydrogen production (Krane 2022). Aramco's current industrial participation is mainly in the petrochemical industry. Over time, its role in the Saudi industrial strategy could expand to that of a provider of clean fuels. In particular, it might use renewables to decarbonize parts of its production processes and venture into carbon capture and sequestration services for steel, aluminum, fertilizer, cement production, and other emission-intensive sectors, domestically and internationally.

Aramco is also central to the Saudi climate strategy in a less direct way, namely, as a leader in leveraging the Kingdom's oil and gas (O&G) for further economic diversification. The Company has invested in researching and developing technologies and creating business units to find climate-compliant uses and markets for hydrocarbon resources. Aramco articulated these ambitions under the low-carbon header of its first-ever sustainability report, which states, '*developing low-carbon products and solutions helps to sustain and diversify demand for oil and gas through competitive technologies*' (Saudi Aramco 2022). The production of low-carbon hydrogen and related fuels is expected to become a part of this diversified portfolio in the future.

Aramco's diversification and decarbonization ambitions face challenges. The costs of Aramco's adherence to the Saudi national climate goal of reaching net zero by 2060 remain unknown. The 2060 goal also awaits the implementation of a national Circular Carbon Economy policy framework. Worldwide, few governments have estimated the cost of reaching net-zero emissions (NZE) by a particular date or presented the necessary policy framework for implementation over the coming decades. This renders most commitments toward any net-zero target hazy and noncommittal.

Currently, Saudi policymakers are pursuing domestic decarbonization by displacing liquids in carbon-based power and transportation with cheaper and cleaner electricity and hydrocarbons. In doing so, the Company encourages increased hydrocarbon exports and revenues, since domestic O&G are sold at domestic prices set below international prices, while exports are priced based on global benchmarks. Outside the Kingdom, however, the success of global climate action hinges on halting or abating GHG emissions from the combustion of petroleum 'molecules' the O&G sold by Aramco (Krane 2022). The transition from combustible fuels to clean electricity and cleaner molecules like hydrogen is pressuring Aramco's revenue. The Company recognizes that the pace of the energy transition will vary between regions and that it will need to adapt to the differing needs of its customer base to remain a global energy player.

Additionally, the signals of Aramco's commitment to diversification and energy transition-related technologies are mixed. On the one hand, the Company has made several announcements that underline its ambitions to become a major player in the market for clean hydrogen. On the other hand, Aramco's capital allocation toward the energy transition lags that of its peers, as it performs carbon accounting throughout the entire value chain, including so-called Scope 3 emissions, or indirect emissions from fuel combustion.

The remainder of this chapter examines Aramco's hydrogen ambitions in the context of the Kingdom's commitment to climate action. Section 'Economic diversification and Aramco's clean hydrogen bet-hedging strategy' investigates the factors driving Aramco and other major oil firms' expansions into decarbonized molecules and technologies as a 'bet-hedging' strategy to strengthen their long-term resilience and reduce the risk of revenue disruption. Aramco's initial actions suggest a competitive presence in emerging markets. Section 'Aramco's hydrogen prospects and project' reviews Aramco's clean hydrogen projects and the factors that distinguish its approach from those of competing supermajors. Section 'Aramco, hydrogen, and the Kingdom's climate action' examines the carbon accounting of direct (Scopes 1 and 2) and indirect (Scope 3) emissions. It also juxtaposes Aramco's role in domestic and international climate action against the uncertainties around gathering and evaluating data on the indirect emissions of its conventional energy production and usage. A central message of the chapter is that accounting for indirect emissions is not only relevant to Aramco's conventional operations but also serves its blue hydrogen ambitions, where carbon transparency will help the firm compete on cost and strict sustainability criteria. Section 'Conclusion' concludes.

Economic diversification and Aramco's clean hydrogen bet-hedging strategy

Economic diversification represents a policy response that addresses the need to reduce GHG emissions to mitigate climate change and economic dependence on threatened fossil fuels (Krane 2020). Diversification involves both broadening exports toward higher-value goods and expanding industrial production capacity. Low-productivity commodity exporters find diversification particularly challenging. Success involves a political commitment to structural economic change and a governance structure that produces high-value end products, human capital, and technological know-how.

Oil exporters must overcome another barrier to contend with the likelihood that diversification tends to reduce returns on investment. The oil sector is a special case in the global economy in which low-cost producers earn outsized economic rents because the marginal production cost is set by higher-cost producers (Smith 2009). The extreme profitability of Gulf oil production is difficult to replicate in other sectors of a diversified economy. For these reasons, and perhaps others, prior attempts at diversification have been lackluster and largely unsuccessful. However, climate action pressures have changed the risk calculus among oil-dominated export states, including Saudi Arabia. The prospect of oil substitutes in transportation and the near-term peak in global oil demand have incentivized more serious efforts (Krane 2020).

As a response to the need for oil-exporting countries in the Middle East and North Africa region to diversify, Poudineh and Fattouh (2020) explain a 'conservative bet-hedging strategy' as lowering investors' best performance under favorable conditions to improve their worst performance under unfavorable conditions. According to the authors, the return on a conservative bet-hedging strategy is lower than that on the current default strategy of (in this case) O&G production and exports given the costs involved and lower margins. However, diversification remains attractive because the risk profile is low.

Utilizing energy carriers such as clean hydrogen and ammonia constitutes a conservative bet-hedging strategy for various reasons. First, they can be produced from hydrocarbons and supported by investment in CCUS. Second, CCUS is very costly, indicating significant room for cost efficiency gains and R&D in this area that can be exploited by producers. Third, during the transition stage, these producers can still export O&G and benefit from the generated rents, while simultaneously improving the return on decarbonized products (e.g., ammonia, hydrogen, alternative low-carbon fuels). Fourth, this strategy requires the continuous improvement of technologies, products, human capital, engineering and design, and patenting laws. Fifth, exports of energy carriers such as hydrogen and ammonia also synergize more closely with businesses built on the supply chain model of fuel exports. By contrast, any shift in strategy away from O&G as inputs, such as renewable generation, implies adopting a less familiar business model. Such a model may also incur large upfront capital investments in infrastructure that operates for decades without combustible fuel or a supply chain (Krane and Idel 2021; Al-Mazeedi et al. 2021).

As oil demand declines and the emphasis on climate mitigation action increases, producers in the Middle East, such as Aramco, are enjoying competitive advantages in hydrogen production. This is because of the region's plentiful resources and geological storage, unused land with copious solar radiation, and O&G infrastructure and expertise (e.g., in subsurface technology) that translate well to hydrogen. Hence, Aramco has a strong opportunity to establish a competitive presence in any emerging hydrogen market (Al Khowaiter and Mufti 2021). First, it is the lowest-cost producer of crude oil and natural gas. Second, it has an integrated and complementary infrastructure at scale at its disposal, including significant know-how in CCUS and a leading position in global ammonia trade acquired through its majority stake in Saudi Basic Industries Corporation (SABIC) (Al Khowaiter and Mufti 2021). Based on these advantages, Aramco has a strong opportunity to establish a competitive presence in any emerging hydrogen market.

Blue hydrogen production could also leverage Aramco's existing investments in CCUS. The Company has investigated carbon sequestration across several projects and initiatives, including one of the world's largest carbon capture and storage plants at Hawiyah in the Eastern Province. The plant at Hawiyah captures 0.8 million tons of CO_2 annually for enhanced oil recovery (EOR). Next to EOR, blue ammonia improves the environmental credentials of the products exported by Saudi produced by reusing the CO_2 captured during the production of hydrogen and replacing conventional fossil fuels. The production and consumption of ammonia are largely localized, and large-scale demand for blue or green ammonia has yet to manifest. This is changing, however, as net-zero targets force governments to address the issue of fertilizers, the fastest growing source of agricultural emissions and foremost source of demand for ammonia (BloombergNEF 2020). Europe was responsible for almost 20% of global fertilizer emissions in 2017 and could become a large market for Aramco (BloombergNEF 2020). Nevertheless, global demand for blue ammonia is expected to grow substantially, and access to cheap domestic gas could give Aramco a competitive advantage.

Another factor encouraging Aramco's hydrogen investment is the probability that demand for hydrogen will increasingly be negatively correlated with demand for oil, but positively with successful decarbonization (IEA 2022). The reverse correlation of demand for hydrocarbons and hydrogen renders investment in the latter attractive as a conservative bet-hedging strategy. This can assist in rationalizing upstream investment (particularly in gas) and provide an alternative and long-lived market for O&G (IEA 2022). In short, the more climate action undermines the combustion of non-abated hydrocarbons, the more it encourages the consumption of clean hydrogen and its derivatives. Table 3.1 shows the uptake of clean hydrogen under three International Energy Agency (IEA) scenarios:

- Stated Policies Scenario (STEPS) shows the trajectory implied by today's policy settings.
- Announced Pledges Scenario (APS) assumes that all aspirational targets announced by governments are met on time and in full, including their long-term net-zero and energy access goals.
- NZE maps out a way to achieve a 1.5°C stabilization in the rise in global average temperatures, alongside universal access to modern energy sources by 2050.

The most attractive of the IEA's three future energy demand scenarios in terms of clean hydrogen uptake is the NZE scenario, which depicts the global attainment of net zero by 2050. Under the NZE scenario, more specifically, total global demand for hydrogen will reach 180 million tons by 2030 and 475 million tons by 2050 (of which 90 million tons in 2030 and 450 million tons in 2050 are low emissions). Electrolyzers will meet a third of this demand in 2030 and 70% in 2050. This requires installed electrolyzer capacity of 720 GW by 2030 and 3,670 GW by 2050. The required wind and solar photovoltaics (PV) generation capacity for

TABLE 3.1 Supply of and demand for low-emissions hydrogen and fuels in 2030 and 2050 under three scenarios: STEPS, APS, and NZE by 2050

Million tons of H_2 eq. (energy basis)	*STEPS*		*APS*		*NZE*	
	2030	*2050*	*2030*	*2050*	*2030*	*2050*
Total low-emissions H_2 production	6	24	30	225	90	452
Water electrolysis	*4*	*17*	*21*	*167*	*58*	*329*
Fossil fuels with CCUS	*2*	*8*	*9*	*57*	*31*	*122*
Bioenergy	*0*	*0*	*0*	*1*	*0*	*2*
Transformation	3	10	14	95	50	186
To power gen.	*0*	*1*	*4*	*19*	*27*	*60*
To H_2-based fuels	*0*	*3*	*6*	*69*	*18*	*118*
To oil refining	*2*	*5*	*3*	*6*	*2*	*4*
To biofuels	*1*	*1*	*1*	*1*	*3*	*3*
Demand by end-use sector	3	15	16	131	40	266
Total final consumption	*1*	*10*	*12*	*80*	*31*	*174*
Onsite prod.	*2*	*4*	*4*	*51*	*9*	*92*
Low-emissions H_2-based fuels	0	3	3	55	15	96
Total final consumption	*0*	*1*	*3*	*39*	*7*	*68*
Power gen.	*0*	*2*	*0*	*16*	*8*	*28*
Trade	1	5	4	44	18	73

Source: IEA (2022)*.*) 1 million tonnes H_2 = 120 petajoules. Transformation to hydrogen-based fuels incurs energy losses that are the difference between hydrogen inputs to hydrogen-based fuels and demand for these fuels.

electrolysis would be of the order of 1,000 GW by 2030 (IEA 2022). Under this scenario, the IEA found an enormous uptake of low-emission fuels such as hydrogen and hydrogen-based fuels, including investments jumping from $18 billion in 2022 to $235 billion per year by 2030. By 2050, these low-emission fuels could account for more than 65% of the total investment in fuels, up from the current 1% (IEA 2022). Despite such optimism, caution is warranted about the extent of hydrogen's likely contribution to the global energy balance, even amid successful decarbonization. The IEA estimates that hydrogen exports will amount to only a 'very partial replacement' for hydrocarbon exports (IEA 2022). This is due to competition from other similarly endowed countries that drive down available resource rents as well as the far smaller size of the projected hydrogen market, high costs, and large efficiency losses (Figure 3.1).

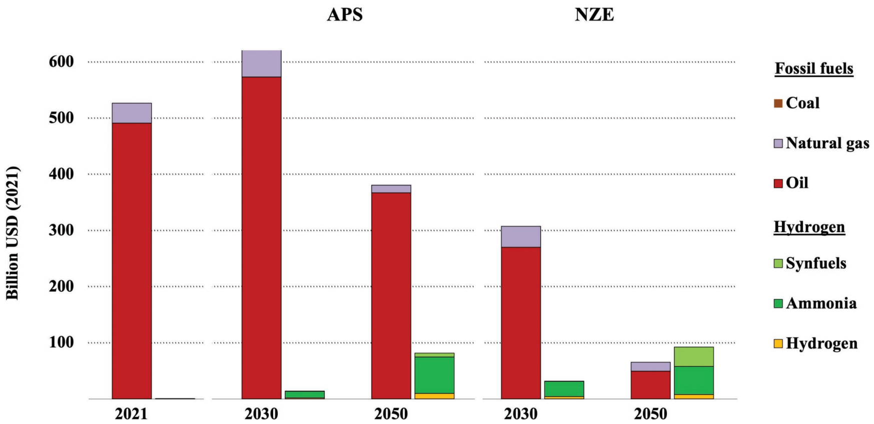

FIGURE 3.1 Export revenue from oil and gas compared with that from hydrogen in the Middle East under the APS and NZE scenarios, 2021–2050*. *) The export revenue from hydrogen and related fuels (yellow and green) does not approach the returns from today's oil and gas exports. The IEA's APS and NZE scenarios predict large shares of hydrogen and clean fuel consumption by 2050, with hydrogen-based fuel consumption eclipsing that of oil under the NZE 2050 scenario.

Source: IEA (2022).

Nevertheless, the IEA argues that hydrogen production remains worthwhile, if not for export rents but for leveraging hydrogen to reach a commanding position in the manufacturing and export of low-emission industrial products and chemicals (IEA 2022).

Aramco's hydrogen prospects and projects

The cost of blue hydrogen in Saudi Arabia is estimated at $1.34/kg using the current price of natural gas at $1.25/MMBtu (Hasan and Shabaneh 2022). With advancements in CCUS technologies, this cost is expected to decrease by more than 15% by 2030. However, despite the decreasing cost of CCUS, the economic viability of blue hydrogen is highly sensitive to natural gas prices. An upward correction in prices can impact the costs of producing blue hydrogen. With green hydrogen estimated to cost $1.48/kg in Saudi Arabia by 2030, blue hydrogen would still be competitive at a gas price of $3.25/MMBtu (Hasan and Shabaneh 2022).

In 2022, Aramco announced a production capacity goal of 11 million tons of blue ammonia by 2030, which would require 1.93 million tons of blue hydrogen produced from natural gas linked to CCUS (Saudi Aramco 2022). This ambition includes developing the CCUS capacity to capture up to 11 $MMtCO_2e$ annually by 2035 (Saudi Aramco 2022). This will contribute to the Kingdom's overarching goal of capturing 44 $MMtCO_2$ annually by 2035. The first phase of this goal is underway, and Aramco has signed an agreement with Linde and SLB to build a

9 $MMtCO_2$ carbon capture and storage hub in Jubail by 2027. However, its blue hydrogen-dominated plans differ from those of other O&G supermajors, which emphasize multiple production methods. While blue hydrogen is the chief focus, Aramco's plans also include investments in renewable and green hydrogen technologies that produce renewable-based hydrogen (Radowitz 2022).

Regarding the Company's primary focus on blue hydrogen, three important challenges must be noted. First, such a focus can give it a head start because it possesses vast knowledge, a well-designed infrastructure, and other capital resources. However, gas production is not infinite and hydrogen producers compete for natural gas with power utilities and the petrochemical industry domestically. Second, an increase in the adoption of ambitious climate policies would strengthen the expected growth in global demand for clean hydrogen (i.e., strengthen the case for green hydrogen) and limit the appeal of blue hydrogen in the long run. Third, it remains difficult to identify off-take agreements in key markets such as Europe and Asia because of the high costs of using blue hydrogen (Collins 2023a). This is because the majority of customers are waiting for government incentives to pursue blue hydrogen, and most subsidies planned or implemented globally are geared toward green hydrogen production and uptake (Collins 2023a). Combined with other challenges such as the lack of a CO_2 market and the limited inroads of CCUS globally, this raises questions about the bankability of blue hydrogen for Aramco in the long run.

However, owing to its gas resources and subsurface pore space, Saudi Arabia's Eastern Province is ideal for producing blue hydrogen. It has a concentration of gas fields, distribution pipelines, and close proximity to potential CO_2 storage and utilization sites (Hasan and Shabaneh 2022). Regarding the possibilities for green hydrogen production, the Eastern Province, particularly the area surrounding Aramco's headquarters in Dhahran, has enormous (and optimal) potential for using electricity generated with wind turbines and PV to produce low-carbon fuels such as hydrogen, sometimes known as 'Power-to-X' (PtX) production (Figure 3.2).

Developing this vast production potential could enable Aramco to build a production capacity similar to (or potentially even greater than) that in the NEOM region in the north-west of Saudi Arabia (see Figure 3.2 and Chapter 5). This capacity could be combined with Aramco's conventional hydrocarbons, making optimal use of its highly developed gas and oil infrastructure in the Eastern Province and beyond.

Globally, Aramco has signed agreements and formed partnerships to explore opportunities for producing low-carbon hydrogen. Most of these agreements focus on the Asian market in which most of the Company's crude oil is sold, including Japan, South Korea, Indonesia, Thailand, and China. In 2019, a memorandum of understanding was signed by the Institute of Energy Economics Japan, with the support of Japan's Ministry of Economy, Trade, and Industry. This resulted in a demonstration shipment of 40 tons of blue ammonia being sent to Japan by Aramco and SABIC in 2020 and paved the way for more blue ammonia shipments.

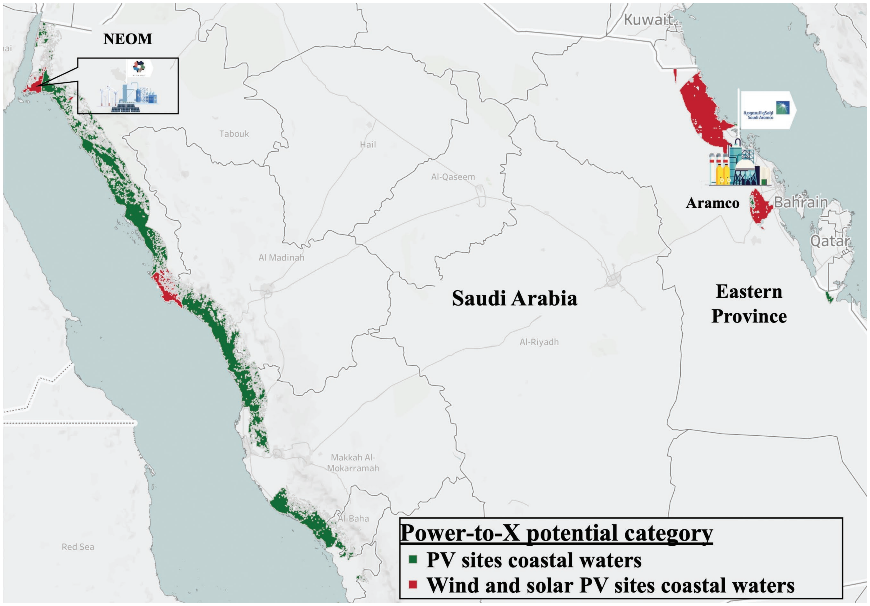

FIGURE 3.2 Geographic Information System–based analysis of the PtX potential in Saudi Arabia by 2050.

Source: Authors, based on Braun et al. (2023) The Fraunhofer Institute for Energy Economics and Energy System Technology IEE (n.d.) Global PtX Atlas considers strict sustainability criteria, including nature conservation and unsuitable areas, land use, and infrastructure. The results show the production quantities and costs of climate-friendly fuel production under strict sustainability criteria and locate them spatially.

Another 25,000 mt of blue ammonia cargo was shipped to South Korea's Lotte Fine Chemicals by the end of 2022. This shipment was the first commercial blue ammonia cargo independently certified as low carbon by TUV Rheinland, an independent inspection and certification service provider (SABIC 2022). To receive the certification, a lifecycle emissions intensity of less than 3.384 kg of CO_2e/kg of hydrogen should be met and at least 30% of total CO_2 emissions must be chemically or minerally fixed for at least 25 years (TÜV Rheinland Standard H2.21 Renewable and Low-Carbon Hydrogen Fuels 2023). The certification was based on a 'cradle-to-gate' emission lifecycle assessment (i.e., it excluded emissions from transportation to the customer).

These shipments highlight Aramco's possibilities for multiparty collaboration across the low-carbon ammonia value chain. Another example is the shipment to Japan's Fuji Oil Company in early 2023 for co-firing ammonia in a gas boiler to generate electricity at the Sodeguara oil refinery. Specifically, this ammonia was produced from Aramco feedstock by SABIC, in which Aramco holds a 70% majority stake. It was then sold by the Aramco Trading Company to an external party and shipped by a designated shipping firm (Saudi Aramco 2023). However, promoting ammonia co-firing and shipping it over long distances in a carbon-intensive manner have raised concerns about whether this is indeed a low-carbon energy solution (Collins 2023b). It has been argued that even with the use of blue or green ammonia, emissions can still result from production, storage, and shipping, which increases lifecycle emissions further if traditional unabated processes are used (Martin 2023). National policymakers tasked with implementing net-zero measures in importing countries such as Japan must therefore create the right incentives beyond the pilot phase of imports to ensure that a shift toward 100% low-carbon ammonia burning in power plants occurs. Sodeguara's power-related emissions could be reduced more easily by installing solar panels on site and using ammonia that the refinery produces as a by-product instead of shipping it halfway around the world (Collins 2023b).

Managed by Aramco Ventures, the Company has also announced the creation of a $1.5 billion sustainability fund to invest in technologies that support oil majors' net zero by 2050 ambition (Saudi Aramco 2022). The aim behind creating this fund is to invest in sustainable energy technologies including carbon capture and storage, hydrogen, ammonia, and synthetic fuels, with targets globally. At the time of writing this chapter, details on the focus and amount of spending on clean hydrogen were not available. However, in a net zero by 2060 scenario in Saudi Arabia, Aramco sees clean hydrogen, carbon offsets, and CCUS as the key means to diversify its product portfolio and mitigate end-user emissions.

Aramco's sustainability report recognizes the possibility of producing hydrogen from multiple energy sources. Nonetheless, hydrocarbons will remain its primary hydrogen feedstock (Saudi Aramco 2022) since the supermajor's core business relates to petroleum 'molecules' rather than electrons. The report also acknowledges the circular carbon economy principles recommended by the Saudi government. The government is aiming to reframe the discourse on CO_2 from one of a negative externality to a proposition that CO_2 has value that can be extracted and commodified (Chapter 2). However, the Kingdom lacks a viable regulatory framework (e.g., the EU Emissions Trading System or US hydrogen tax credit regime) that might incentivize the scaling up of blue hydrogen in the Gulf (Al-Mazeedi et al. 2021).

Aramco, hydrogen, and the Kingdom's climate action

While conflicting economic and environmental interests exist in all economies, they are more pronounced in polities that derive a large share of their public budgets from fossil fuel exports. However, Aramco recognizes that some countries will undergo an energy transition faster than others. Saudi policymakers see potential advantages in transitioning the Saudi economy as part of its Vision 2030 diversification goals. On a per-barrel basis, Aramco has some of the lowest Scopes 1 and 2 carbon emissions among national and international oil companies (National oil companies, NOCs and International oil companies, IOCs, respectively hereafter). Scope 1 covers the direct emissions from a company's own combustion. Scope 2 covers indirect emissions from the acquisition of electricity from the power grid (Götz et al. 2017).

In a world still reliant on hydrocarbons, Aramco has a competitive advantage in terms of both production costs and upstream carbon intensity. The latter is due to low per-barrel natural gas flaring rates, low fugitive methane emissions, and low water production. This means that less mass lifted per unit of oil produced and less energy for fluid separation and handling are required (Masnadi et al. 2018). As part of Aramco's abatement plans, it is striving to reduce its Scopes 1 and 2 emissions to net zero. Hence, it is focusing on measuring emissions from its own operations and electricity consumption. However, it is disregarding the emissions flowing from the consumption of Aramco products beyond company premises as well as those from transport, distribution, and conversion off site (Scope 3) (Saudi Aramco 2022).

In a well-to-wheel CO_2 lifecycle, Scope 3 emissions usually account for 80%–95% of total carbon emissions from O&G use. While the government and public stakeholders are pushing NOCs to be more rigorous and transparent with their emissions disclosures, only a handful of O&G companies globally have included Scope 3 emissions in their net-zero targets (Wood Mackenzie 2022). Aramco's emissions were responsible for approximately 4.8% of total GHG emissions from the oil sector in 2018 and approximately 4.3% of the total atmospheric accumulations since 1965. Both these shares were the largest for any single firm (Climate Accountability Institute 2020). Figure 3.3 reveals that most of Aramco's emissions were Scope 3 emissions in 2015.

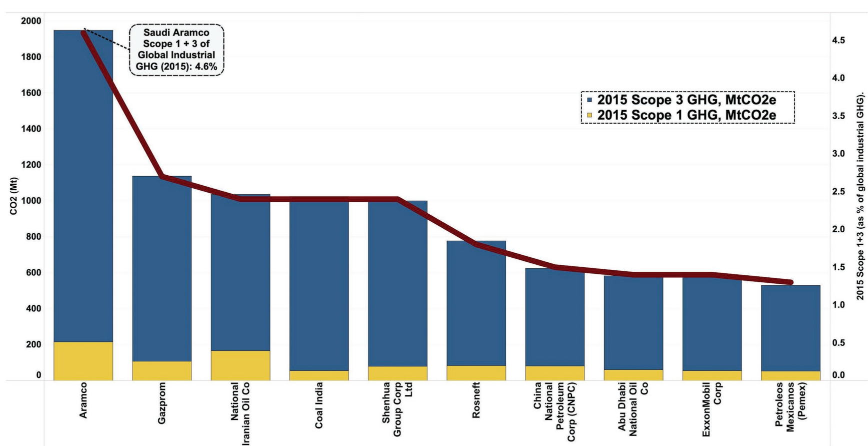

FIGURE 3.3 Top 10 fossil fuel companies in 2015 by operational (Scope 1) and product (Scope 3) GHG emissions.

Source: Authors, adapted from Griffin (2017)*.*) The y-axis on the left shows CO_2 emissions (million tons), and the y-axis on the right (represented by the red line) shows Scopes 1 and 3 as a percentage of global industrial GHG emissions.

Focusing on Aramco's carbon accounting and the composition of its emissions is important in the context of the validity of Saudi Arabia's climate action and hydrogen ambitions. Next to phasing out coal, the success of global climate action depends heavily on reducing or offsetting GHG emissions from the combustion of

O&G. However, for O&G companies, Scope 3 emissions are more difficult to collate and evaluate than Scopes 1 and 2 emissions because many of the activities fall outside the company's operations. Thus, estimates of Scope 3 emissions may be inaccurate and highly uncertain (IPIECA and API, 2016). In addition to data reliability, avoiding 'double counting' is another challenge to ensuring the accuracy of calculating Scope 3 emissions. Care should be taken to ensure that reported emissions are not counted multiple times across interconnected supply chains, which could inflate the perception of the carbon risk (Shrimali 2021). However, despite these challenges, Scope 3 emissions are too large to ignore, and companies must engage with value chain partners, including customers and accounting firms, to measure them accurately. This can enable Aramco to position itself as a provider of clean energy.

Clean hydrogen as an energy carrier, in this case, from natural gas and CCUS, can provide energy companies such as Aramco with a solution to their Scope 3 emissions. No CO_2 is emitted when using clean hydrogen during combustion, and the majority of emissions can be captured within the company's facilities. Accelerating investments in CCUS technologies, including direct air capture, could further enhance Aramco's ability to deal with Scope 3 emissions, both domestically and globally. However, emissions from the conventional value chain are also related to hydrogen. As the clean hydrogen economy develops, the need for increased and inclusive measurement, reporting, and verification is important for verifying and certifying the sustainable features of the hydrogen being produced and traded. Figure 3.4 illustrates the supply chain for natural gas-based hydrogen, including the boundaries set by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology.

The IPHE is an intergovernmental body working to reach a consensus on a universally accepted methodology for measuring the GHG emissions from clean hydrogen value chains. This methodology is being established as an International Organization for Standardization standard. Figure 3.4 shows the boundary of the

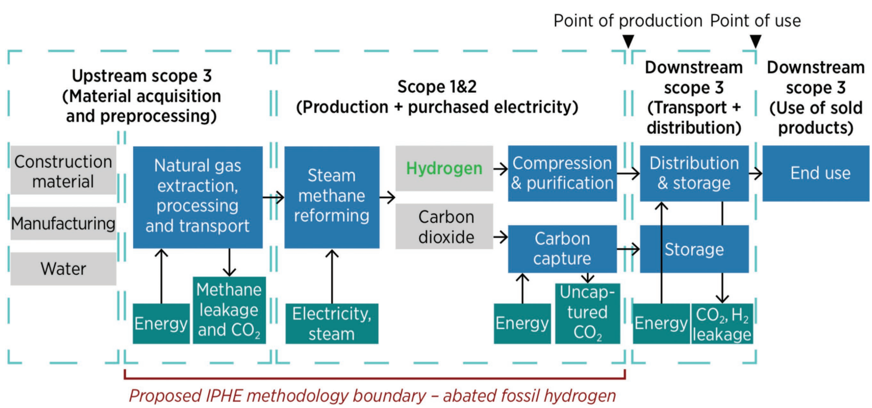

FIGURE 3.4 Supply chain and system boundary for natural gas-based hydrogen.

Source: IRENA and RMI (2023).

IPHE methodology for natural gas-based hydrogen carbon accounting, which includes upstream and midstream emissions from natural gas extraction and processing and downstream emissions from compressing and purifying hydrogen. To have a meaningful impact, the boundary must eventually be expanded to incorporate a comprehensive lifecycle analysis (well-to-wheel), in which the conversion, transportation, and distribution of hydrogen are considered, and guarantee CO_2 containment in geological formations. Taking stock of its Scopes 1–3 emissions is not only relevant for Aramco's conventional operations but also serves its blue hydrogen ambitions; this is because the Company will have to compete on cost and sustainability criteria while accounting for emissions throughout the value chain.

Beyond carbon accounting, there are signs that oil supermajors have missed opportunities to demonstrate their commitment to climate action. Governments and executives linked to large utilities and energy firms have spent the past few decades voicing or funding opposition to climate action, while continuing to invest in the exploration and production of O&G (Depledge 2008; Bohr 2016; Culhane, Hall, and Roberts 2021). Few producers have diversified their capital investments into renewables, clean hydrogen, or even carbon capture and storage, given the reduced (or negative) rates of return for these fossil fuel options.

Owing to drivers such as emerging carbon pricing instruments and shareholder pressure, the investment response of oil companies and producer states to climate change continues to be dominated by IOCs. Many have already begun diversifying capital investment into non-oil businesses in clean electricity, carbon offsets and trading, and electric vehicle charging. Shareholder-owned oil majors were estimated to have allocated \$15 billion—some 15% of their capital budgets—toward low-carbon ventures in 2022, with European IOCs allocating around 20%. Capital guidance from NOCs was far less: \$5 billion was allocated, which amounted to less than 5% of capital budgets on average (Figure 3.5).

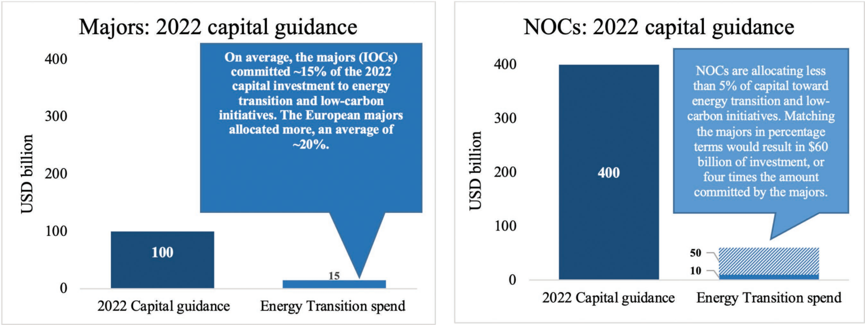

FIGURE 3.5 NOCs lag the majors in committing capital toward energy transition*.

Source: Portela (2022).*) Low carbon / energy transition capital guidance is provided by only a select few NOCs – PetroChina, Sinopec Corp, CNOOC Ltd, Rosneft, Petrobras, Ecopetrol, Pertamina, PTTEP and Petronas.

Over the past years, there have been signs of accelerating the pace of investment across O&G companies. A recent assessment of the low-carbon ambitions of 17 O&G companies, i.e., six integrated energy companies (IECs), three IOCs, Aramco, and seven other NOCs, notes an accelerating pace of investments in this area (Haris et al. 2022). From 2017 to 2022, the 17 companies invested approximately 74 billion USD in low-carbon solutions. Unsurprisingly, the six IECs (BP, Chevron, Eni, ExxonMobil, Shell, and TotalEnergies) contributed to about 80% of low-carbon investments over this period and are estimated to continue to dominate investment activity. Based on an extrapolation from companies' public statements of commitment, this investment activity could reach 134 billion USD in 2026. The contribution of NOC spending on low-carbon investments could more than triple during the same period (Figure 3.6).

From 2017 to late 2022, O&G companies focused mainly on building renewable power capabilities, dominated by solar and wind. Yet this situation is

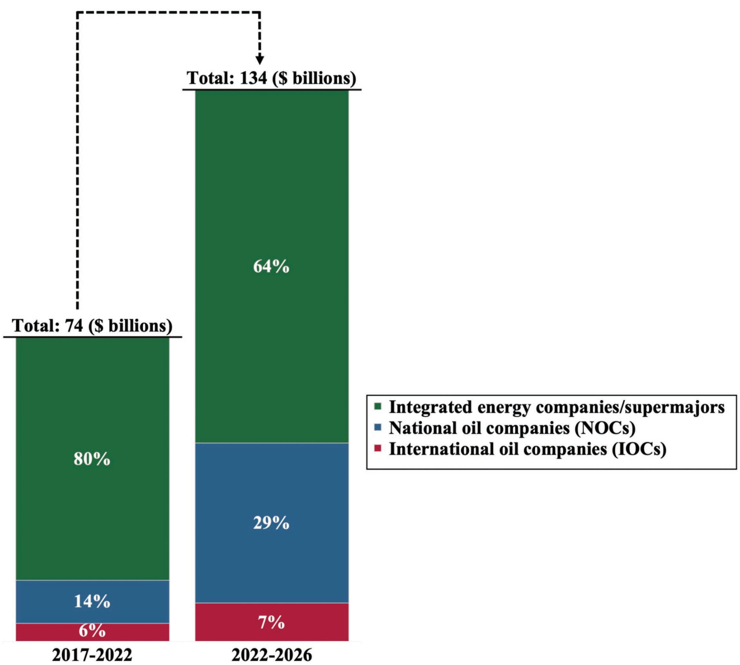

FIGURE 3.6 Selected oil and gas companies* estimated spending on low-carbon investments (2017–2026).

Source: Haris et al. (2022).*) 17 companies are assessed here, including sic EICs/supermajors, eight NOCs, and three IOCs. Aramco is not explicitly mentioned in the publication but is one of the eight NOCs analyzed here (correspondence with author Ilshat Haris [Boston Consulting Group, BCG], 4 October 2023).

changing rapidly as mergers and acquisitions and activity in the venture capital space of O&G companies indicate that clean hydrogen and CCUS are quickly taking center stage (Haris et al. 2022). As exemplified by Aramco's sustainability fund, the shift in these areas of O&G companies' low-carbon investments reflects the importance of hydrogen and CCUS for reaching net-zero goals and achieving synergies with existing assets and operations; it also underlines that they are positioning themselves to become market leaders in low-carbon hydrogen technologies.

For the moment, however, most NOCs, including Aramco, have made declaratory statements and set emissions goals, while others, including Abu Dhabi-based Abu Dhabi National Oil Company (ADNOC), Mexico's Petroleos Mexicanos (PEMEX), Qatar Energy, and Gazprom, have made few or no commitments. And the dichotomy between the energy transition spending of IOCs and NOCs is paradoxical. NOCs produce more petroleum—roughly 60% of the world's oil—and their operations release more GHGs than those of IOCs. However, they have made fewer climate commitments and their emissions and decarbonization plans face less scrutiny; they also have less exposure to litigation and policy risk than IOCs. Much of this is owing to the protection provided by sovereign ownership and lack of exposure to activist shareholders. The importance of oil for government stability is another key factor. Unlike those of IOCs, NOCs' portfolios are relatively inflexible. While most NOCs acknowledge the need for environmental, social, and governance reporting and disclosure to enhance their sustainable value creation strategy, they must also balance low-carbon investments by realizing national economic development and providing access to affordable energy (Johnston, van Heusden, and Razak 2022). The Natural Resource Governance Institute describes more than two dozen countries as budgetarily dependent on export rents from NOCs (Heller and Mihalyi 2019).

The announcement of Saudi Arabia's national net-zero target by 2060 shows that the government is getting to grips with the required targets for implementing the energy transition and recognizing that countries, particularly those within the customer base of Aramco, are willing to pay a premium for cleaner fuels. This recognition is also visible in terms of Aramco's capital allocation to decarbonization.

Conclusion

Aramco is the largest commercial entity producing carbon-based fuels worldwide, and the combustion of its O&G accounts for a substantial proportion of global emissions. Therefore, the announcement of a net-zero target at the national (2060) and corporate (2050) levels is the first step toward the success of both Aramco and Saudi Arabia's climate action. The ambition and rigor accompanying the implementation of policy frameworks (e.g., Saudi Arabia's national Circular Carbon

Economy program) and Aramco's sustainable governance efforts, for example in fora as the Oil and Gas Climate Initiative, will be crucial in determining the success of these net-zero targets (Oil and Gas Climate Initiative n.d.) over the coming decades.

Investing in and promoting energy carriers such as clean hydrogen constitute a conservative bet-hedging strategy for Aramco, as it leverages expertise and legacy assets to produce low-carbon products. Aramco's 2021 sustainability report suggests that developing low-carbon products and solutions such as hydrogen will help sustain and diversify demand for O&G by using competitive technologies. The Company's emphasis on blue hydrogen clearly fits this strategy, as it implies a long-term climate-compliant market for natural gas. Simultaneously, its plans include investments in renewable-based hydrogen, and accompanying technologies also appear opportune given the favorable geographic and geological conditions. One example is Saudi Arabia's Eastern Province, where a large and concentrated area shows huge potential for the optimal production of renewable hydrogen.

Aramco, given its majority ownership stake in SABIC, is well positioned as a global leader in hydrogen and its derivatives. Not only will hydrogen add to its export portfolio but it will also provide an edge in monetizing and expanding its CCUS technologies. Both will be key factors in achieving the Company's NZE target and that of the Kingdom. Aramco's challenge is to balance its legacy business model to supply traditional fuels while developing new offerings of cleaner products. Aramco's ventures in clean hydrogen also imply that the Company is following the path of many O&G majors to become a provider of all energy rather than just O&G. The $1.5 billion sustainability fund alongside Aramco's R&D will allow it to start acquiring breakthrough low-carbon technologies and remain agile in an uncertain future environment.

However, the new business model outlined herein remains uncertain. The major shift toward hydrogen and its derivatives involves expensive and complex commercial, trade, and regulatory aspects as well as capacity building and technology development. Simultaneously, Aramco's preferred path toward clean energy must compete with cheaper and more viable pathways that grow quickly. These include renewable power generation and other clean technologies such as nuclear power and battery storage.

Finally, NOCs lag IOCs when it comes to low-carbon capital spending owing to their differing mandates and shareholder and stakeholder pressures. While disclosure is improving, reporting the major source of emissions, namely, those of its customers or Scope 3 emissions, remains a huge task. Taking stock of its Scope 3 emissions is not only relevant for Aramco's conventional operations but would also help meet its clean hydrogen ambitions. In addition, Aramco must compete on costs, strict sustainability criteria, and transparent carbon accounting throughout the value chain, even though clean hydrogen is a very different commodity from conventional fuels.

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4

SABIC'S PATHWAY TO CARBON NEUTRALITY AND THE ROLE OF HYDROGEN

Abdulaziz Al Jodai, Pieter Smeets, Fahad Al Sherehy, and Hicham Idriss

Introduction: SABIC's global petrochemical play

Saudi Basic Industries Corporation (SABIC) is the third largest petrochemical company in the world, headquartered in Riyadh and operating in 50 countries. SABIC was established in 1976 under a Royal Decree as a joint-stock company with 70% of its shares owned by the Saudi government and the remainder held by public investors (Sabic 2006). The primary reason for its establishment was to ramp up the Kingdom's petrochemical, fertilizer, and metal manufacturing capacity and to ensure that manufactured products meet domestic demand and enter the export market (Sabic 2006).

In 2020, Saudi Aramco acquired the government's shareholding in SABIC through the Kingdom's Public Investment Fund. The acquisition aimed to leverage domestic synergies, as Aramco supplies SABIC with its natural gas feedstock. It also aimed to strengthen Saudi Aramco's competitiveness in international petrochemical markets by accessing SABIC's global research and marketing capabilities (Sabic 2020). Additionally, the acquisition helped SABIC, which can now take advantage of Aramco's financial heft to become more competitive globally.

SABIC operates through three strategic business units (SBUs), namely, petrochemicals, agri-nutrients, and specialties, and one standalone organization, the Saudi Iron and Steel Company, known as Hadeed (Sabic 2020).

- The petrochemicals SBU focuses on the manufacturing, distribution, and sale of commodity and performance chemicals as well as polymers (Sabic 2021). It accounts for the largest proportion of SABIC's production and sales volumes, namely 79% and 78% of the total in 2021, respectively (Sabic 2021). With almost 86% of total revenue, it is the main contributor to SABIC's bottom line.

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- The agri-nutrients SBU covers the manufacturing, distribution, and sale of fertilizers and specialty inorganic products for plant nutrition (Sabic 2021). SABIC is the largest exporter of granular urea globally and the sixth largest producer of ammonia worldwide (Sabic 2021).
- The specialties SBU handles the manufacture, distribution, and sale of plastics, which are typically customized to meet unique and complex specifications (Sabic 2021).
- Hadeed is involved in the manufacturing, distribution, and sale of long flat steel products (Sabic 2021). It is the largest integrated steel producer in the Gulf region, with a crude steel production capacity of 6 million tons (Kinch et al. 2020).

International sales generated nearly 83% of SABIC's 2021 revenue of $46.64 billion (Sabic 2021). As the largest non-oil industrial company in the Middle East, SABIC plays a crucial role in the Kingdom's industrial economy (Sabic 2020).

Sustainability as a business strategy

SABIC was established to use the Kingdom's natural gas as a feedstock for the manufacture of petrochemical products. At that time, the natural gas associated with oil extraction was underutilized and flared at wellheads (Sabic 2021). The Kingdom aimed to build export-oriented petrochemical plants close to its natural gas resources, thus diversifying the economy away from oil exports (Sabic 2020). Accordingly, the core business of SABIC is manufacturing chemicals from the constituents of natural gas such as methane, ethane, and propane. SABIC uses methane to produce methanol, ammonia, and urea. Ethane and propane are used to manufacture the building blocks of plastic materials such as olefins, glycols, polyethylenes, polypropylenes, and polycarbonates. However, after acquiring manufacturing assets elsewhere in the world, SABIC's current production processes also rely on other hydrocarbon feedstocks such as butane and light naphtha (Sabic 2020). Regardless of the feedstock, SABIC products have a vast range of applications, from household items to packaging to specialty materials.

Since its initial operations in the Kingdom, SABIC has grown—both organically and through overseas acquisitions—into one of the world's largest integrated petrochemical companies. Sustainability has always been crucial to SABIC's identity. It was recognized early that global environmental constraints would influence its strategy (Sabic 2021). Acknowledging the environmental issues associated with petrochemicals and providing solutions is crucial to its operating philosophy (Sabic 2021). For SABIC, sustainability is therefore a 'foundational element' focused on environmental, social, and governance (ESG) principles (Sabic 2021) aligned with its core values and growth ambitions, particularly in European and US markets (Sabic 2021).

FIGURE 4.1 SABIC's materiality priorities.

Source: Sabic Sustainability Report 2018 Executive Summary. (KPI– Key Performance Indicators; GRI – Global Reporting Initiative; EHSS- Environment and Human Health, Safety, and Security).

SABIC periodically conducts risk/opportunity analyses of the elements most important to customers and stakeholders. Such analyses help focus resources where they are deemed to be material to the company's success (see Figure 4.1).

These materiality analyses enable SABIC to develop a sustainability strategy that manages the most critical risks for its business units, customers, and stakeholders, even as it grows (Sabic Sustainability Report 2021). Since 2014, SABIC has engaged with the United Nations over its Clean Development Mechanisms to combat climate change. For example, its Al Jubail Fertilizer Company (AlBayroni) has received carbon credits for its greenhouse gas (GHG) emission savings (Sabic 2018). Similarly, SABIC's global headquarters in Riyadh have been certified as a carbon-neutral site (Sabic 2019).

SABIC aims to improve its wider sustainability performance by aligning its efforts with the United Nations' Sustainable Development Goals. It has identified 10 of the 17 Goals as the most relevant to its business operations and tracked its performance against these goals (SDG Roadmap 2019).

With the company's focus on sustainability, SABIC materials and solutions support the development of societies with moderate per-capita energy consumption. Examples include insulation materials (reducing the energy consumption of buildings) and lightweight assemblies for transportation (reducing per-kilometer fuel consumption and therefore carbon emissions). Other materials include packaging materials (ensuring a longer shelf life of food) and the materials required to manufacture the solar panels, wind turbines, and batteries of renewable energy systems.

SABIC is a member of several international and industry groups addressing many issues of sustainability, including the United Nations Global Compact, World Business Council for Sustainable Development, Plastics Europe, and World Economic Forum's Industry Partnership for Chemicals. It also actively collaborates with industrial peers to develop sustainable technology. SABIC was a founding member of both the World Economic Forum's Low-Carbon Emitting Technology program (Sabic 2021) and the Alliance to End Plastic Waste (Sabic 2019).

SABIC applies innovative technology to make its products and services more sustainable for customers. Indeed, a crucial part of its sustainability initiative is the extensive array of solutions marketed under its TRUCIRCLE™ trademark (Figure 4.2). Launched in 2019, TRUCIRCLE aims to tackle the issue of plastic waste by using a circular carbon economy (CCE) framework to close the value chain linking plastic production, usage, consumption, and waste management.

TRUCIRCLE's solution portfolio can be applied to facilitate the reduction, reuse, recycling, and removal of carbon, as embodied chiefly in plastics. It includes products manufactured from a feedstock derived either from biomass, such as wood pulp (Sabic 2019), or from used plastics, such as mechanically and

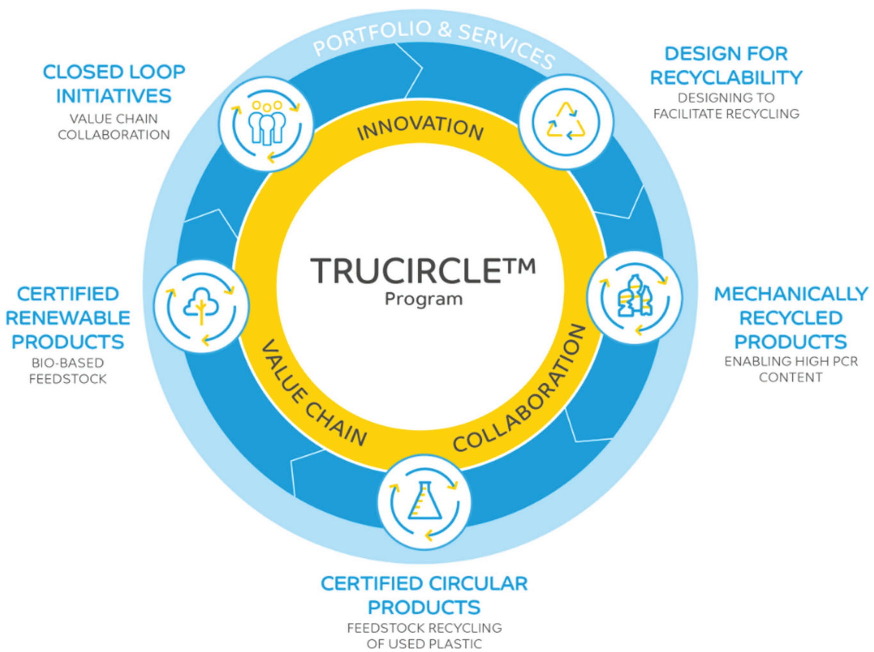

FIGURE 4.2 SABIC's TRUCIRCLE™ process.

Source: Sabic (2019).

chemically post-consumer recycled waste. The renewable or recycled feedstocks of TRUCIRCLE products have been independently certified.

In 2019, SABIC was the first company to manufacture polycarbonates from certified renewable feedstocks (Sabic 2019). It works closely with industry partners and the International Sustainability and Carbon Certification (ISCC) Association. For instance, it has produced certified circular polymers using recycled mixed plastic waste and renewable feedstock (Sabic 2020). In June 2022, SABIC received ISCC Plus accreditation for its polypropylene compounds and resins based on bio-renewable and advanced recycled feedstocks (Sabic 2022). The ISCC Plus certification is based on a 'mass balance system.' Hence, for each ton of circular feedstock fed into the process cracker as a substitute for fossil-based feedstocks, approximately one ton of the resulting output can be classified as circular plastic (Sabic 2021).

A recent lifecycle analysis by SABIC examined the carbon flows of its certified-renewable polypropylene compounds 'from cradle to gate' and 'from cradle to gate plus end-of-life.' This showed that they can reduce fossil fuel consumption by up to 40% and help reduce the carbon footprint of their applications by up to 95% (Sabic 2022).

Decarbonizing the chemical sector

The chemical industry is the largest consumer of energy, mainly in the form of oil and gas (Bellona Europa 2019). A substantial proportion of the consumed energy is due to process needs (e.g., heating large chemical units), which results in carbon emissions. However, most of the carbon in the consumed energy ends up in the industry's products and is not immediately released into the environment. Hence, although the industry accounts for almost 30% of global industrial energy demand, it contributes only approximately 20% of global industrial GHG emissions (Hasanbeigi 2018; Macleod 2021).

The synthesis of ammonia illustrates the difficulty in decarbonizing the chemical industry. Ammonia is typically synthesized by reducing molecular nitrogen using hydrogen. However, the hydrogen for this chemical reaction is produced from natural gas through steam methane reforming (SMR). Based on the underlying stoichiometry, the process releases 5.5 kg of CO_2 per kg of hydrogen produced (Worrell et al. 2000). Nonetheless, when the energy required to drive the process is considered, the total CO_2 released increases substantially. The median release is approximately 9 kg of CO_2 per kg of hydrogen. Indeed, depending on the process and location, it can rise as high as 12 kg of CO_2 per kg of hydrogen (Sun and Elgowainy 2019; Blank and Molly 2020).

Replacing SMR-hydrogen with renewable hydrogen (e.g., made from the electrolysis of water with solar power) is a technically feasible method to decarbonize ammonia synthesis. However, this would be an expensive approach given current renewable energy costs. The non-subsidized levelized cost of hydrogen made from water using fully renewable sources is approximately $5/kg, three to five times higher than that produced from SMR (Khan et al. 2021). Capturing and sequestrating the CO_2 in the SMR process, while expensive, is a more economical approach in the short term as long as sequestration relies on safe and well-proven technology. Therefore, injecting CO_2 deep into subsurface geological formations is being studied extensively (Davarazar et al. 2020).

As one of the world's largest chemical companies, SABIC consumes considerable energy and resources to produce, transport, and sell its products (Sabic 2020). However, to thrive and grow in an intensely competitive and increasingly transparent global business environment, it must demonstrate industry leadership in addressing sustainability challenges.

To overcome the many challenges involved in decarbonization, SABIC is aiming to reduce its CO_2 emissions on multiple fronts. This includes using renewable energy for chemical processes, producing hydrogen with a low CO_2 footprint, and curbing CO_2 emissions in general. Simultaneously, it is focusing on maintaining and improving its operating standards and ensuring cost efficiency as part of its business strategy. In combination, these efforts should improve resource and carbon efficiency as well as increase productivity per unit of feedstock (Sabic 2020).

In 2010, SABIC announced its first sustainability target, namely, to reduce its energy intensity and GHG intensity metrics (GJ and tCO_2e per ton of sales, respectively) by 25% by 2025. SABIC completed its first comprehensive quantification of GHG emissions and energy consumption across its manufacturing sites in 2010, which is why this year was chosen as the base year (Sabic Sustainability Report 2011). By 2021, SABIC had decreased its energy intensity by 11.3% and its GHG intensity by 17.5%, showing progress toward its target (Sabic 2021). These decreases came about from closing the olefin plant in Teesside, UK, as well as restructuring operations and process improvements at the Ibn Rushd plant. Installing energy-efficient systems in other SABIC plants has also helped. Overall, SABIC has managed to reduce its emissions from flaring by 51.1% compared with the 2010 level (Sabic 2021).

Transitioning to carbon neutrality

The global business landscape has drastically changed since 2010. Today's customers, investors, regulators, and consumers increasingly expect more ambitious sustainability strategies and stronger ESG accountability. At the same time, the ESG ecosystem is highly complex, involving many players with inconsistent approaches and a lack of standardization. ESG rating and ranking methodologies differ in what is included and the data sources used. Despite recent efforts to create consistent disclosure standards and metrics, companies have largely been left to their own devices to define how to measure ESG performance and what information is essential. SABIC, for one, has implemented an ESG governance structure that will enable it to provide greater accountability and transparency about its operations.

Part of SABIC's governance structure revolves around setting targets for its new holistic strategy to become carbon-neutral. In October 2021, after HRH Crown Prince Mohammed bin Salman announced the Kingdom's pledge to achieve carbon neutrality by 2060, SABIC committed to achieve carbon neutrality across its worldwide operations a decade sooner (Sabic 2021). In the interim, SABIC is aiming to reduce its Scope 1 and 2 emissions worldwide by 20% by 2030 (relative to 2018), while collaborating with value chain stakeholders for initiatives to reduce indirect Scope 3 emissions (Sabic 2021). In 2021, SABIC's global GHG emissions (Scope 1 and 2) amounted to 51 million mtCO_2eq and its Scope 3 emissions were estimated to be 117 mtCO_2eq (Sabic 2021).

SABIC's 2050 carbon neutrality roadmap (Figure 4.3) delineates five pathways toward its carbon neutrality goal (Sabic 2021):

- Improving reliability and energy efficiency
- Deploying renewable energy
- Electrifying process equipment
- Exploiting opportunities for carbon capture, utilization, and sequestration (CCUS)
- Using green and blue hydrogen

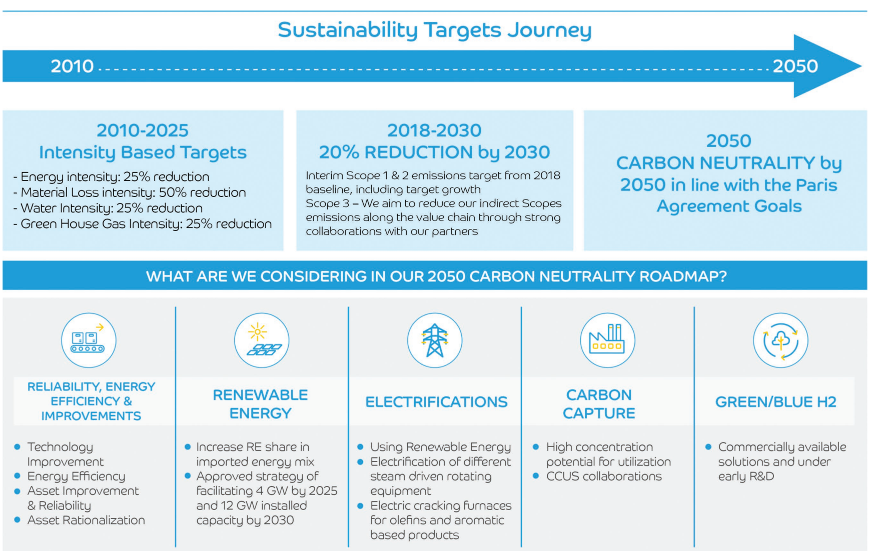

FIGURE 4.3 SABIC's 2050 carbon neutrality roadmap.

Source: Sabic (2021).

These five pathways are aligned with SABIC's broader approach to sustainability and enhance its ongoing progress toward its energy and GHG intensity goals. They can also fit into the CCE framework,[1] which the Kingdom introduced to G20 countries when it held the group's presidency (see Chapter 2). The CCE comprises the 4Rs of reuse, reduce, recycle, and remove carbon (Sabic 2020).

Figure 4.4 depicts how SABIC can reduce, reuse, and recycle CO_2 according to the CCE framework. The illustrated scheme revolves around the world's largest CO_2 capture and purification plant, which a SABIC affiliate has been operating since 2015 in Jubail, Saudi Arabia. This plant has a purification capacity of up to 500,000 mt per annum (Sabic 2020).

The plant captures CO_2 from the ethylene glycol process. After purification, it is injected into a CO_2 pipeline grid that feeds SABIC-affiliated manufacturing facilities, which then use CO_2 to manufacture value-added products such as urea, methanol, and oxy-alcohols. Liquid CO_2 from this plant is used in food and beverage applications (Sabic 2021).

In its sustainability report of 2021, Saudi Aramco stated its ambition to produce 11 million tons of blue ammonia per annum by 2030 (Aramco 2022). This has implications for SABIC since it would play a critical role in any future blue ammonia exports from the Kingdom. SABIC is striving to develop the global low-carbon ammonia market given its extensive expertise in ammonia production, marketing, and downstream production as well as its experience in CCUS. SABIC's agri-nutrients is the leading SBU in these efforts (Sabic 2021).

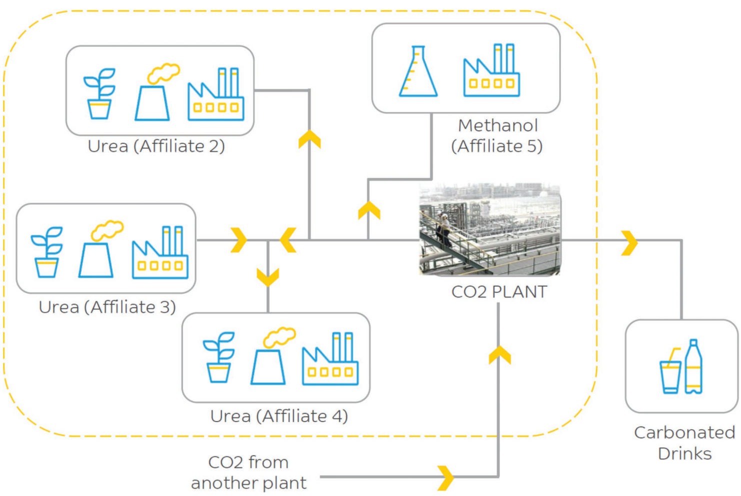

FIGURE 4.4 CO_2 purification and utilization network in SABIC.

Source: Authors.

Green electricity for decarbonization

Electrification is one of the main approaches for curbing CO_2 emissions, provided that electricity is generated from renewable energy. For this reason, SABIC has established short- and long-term goals to significantly increase the company's electricity demand. In the short term, well-established equipment with high technological readiness levels (e.g., rotating equipment) will be electrified. The next phase will involve the electrification of energy-intensive processing units such as steam crackers and reformers for olefin, methanol, and ammonia synthesis. In preparation for this second phase, in 2021, SABIC signed an agreement with BASF and Linde to jointly work on electrically heated steam cracker furnaces. Using renewable electricity, CO_2 emissions from such crackers can be reduced by up to 90% (Sabic 2021).

These electrification goals must be matched with access to renewable energy sources. Therefore, SABIC has formulated a renewable energy roadmap to harness 4 GW of installed generating capacity (comprising wind and solar) by 2025, reaching 12 GW by 2030 (Sabic 2021). A memorandum of understanding between SABIC and the Saudi Ministry of Energy to develop renewable energy projects should help meet those targets (Al-Awsat 2021). However, additional renewable electricity will be required.

Fortunately, SABIC's global footprint opens up possibilities in other countries. It has already installed solar panels at the manufacturing sites in Baroda, India and Rayong, Thailand (Sabic 2021). By 2024, SABIC's polycarbonate-manufacturing facility in Cartagena (Spain) will run on renewable electricity generated by a 100-MW solar photo voltaic facility (Sabic 2020).

Hydrogen as a feedstock and as a fuel

Three chemical processes make the most intensive use of hydrogen at SABIC: methanol synthesis, ammonia synthesis, and steel production. To decarbonize these processes, both blue and green hydrogen will be needed. The main economic drivers for blue hydrogen are the price of natural gas and cost of CO_2 capture and storage, although the latter will become cheaper as its deployment globally rises. The main economic drivers for green hydrogen are the price of renewable electricity and upfront capital expenditure for electrolyzers. As early as 2030, green hydrogen costs could be competitive with those of gray and blue hydrogen on the back of technological improvements and lower renewable electricity costs (Sabic 2021). In Saudi Arabia, renewable energy resources (solar and wind energy) have gained substantial momentum. Recent solar projects conducted by the Ministry of Energy have resulted in competitive renewable electricity generation costs.

SABIC intends to follow a dual blue and green approach to access low-carbon hydrogen. Steam methane reformers would produce blue hydrogen using natural gas while sequestering the CO_2 by-product. In the long run, green hydrogen will be produced from water using renewable electricity. NEOM, an under-construction zero-carbon urban development in Saudi Arabia, provides the best example of the promise of green hydrogen in the country (Arab News 2020).

In addition to green and blue hydrogen, turquoise hydrogen is another alternative for manufacturing net-zero hydrogen. Turquoise hydrogen is based on the pyrolysis of methane, which yields hydrogen and solid carbon (Sanchez-Bastardo et al. 2020). This process is significantly more energetically economical than water electrolysis. It may also be more commercially viable if low-cost natural gas is available. Unfortunately, a large amount of carbon is produced. Each kilogram of hydrogen contains 3 kg of carbon. For this reason, a market that can absorb substantial amounts of carbon by-products must be created. Otherwise, the carbon would need to be stored/sequestered in the geosphere in opencast pits.

Methane pyrolysis technology is not yet ready for large-scale applications. Nevertheless, turquoise hydrogen production could serve as a stopgap until sufficient cost-competitive renewable energy exists for manufacturing green hydrogen. SABIC is closely following the progress of the methane pyrolysis technology for industrial applications.

Hadeed, SABIC's wholly owned integrated steel producer, uses the directly reduced iron-electric arc furnace (DRI-EAF) process to produce steel (Sabic 2021). Hadeed's DRI facility uses hydrogen-rich syngas as the reductant, which is produced from natural gas via SMR. Therefore, Hadeed's decarbonization depends on blue hydrogen as a reductant (and fuel), whereas its EAF needs to be supplied with renewable electricity.

In addition, SABIC is exploring other applications for low-carbon hydrogen. In the United Kingdom, for example, SABIC is converting its ethylene cracker in two phases. The first phase will see a reduction in carbon emissions of approximately 60% through the conversion of its mixed feed cracker to an ethane feed. In the next phase, the project is exploring using blue hydrogen as a fuel for a carbon-neutral cracker (Weddle 2021).

At SABIC's Geleen site in the Netherlands, hydrogen offers an innovative way of closing the value chain 'loop,' as envisaged by the CCE. The oils from the pyrolytic breakdown of low-grade mixed plastic waste are hydrotreated to be used to make olefins for polymers (Albasini 2022). Hydrotreatment helps remove impurities and enrich the hydrogen-to-carbon ratio of pyrolysis oils. The removal of impurities also enables a significantly more energy-efficient reaction to take place. Using low-carbon hydrogen in this process not only reduces the carbon intensity of the polymer production process but also closes the loop on plastic waste.

Underlining its business interest in renewables-based hydrogen production, SABIC recently joined the Hydrogen Council, a global CEO-led initiative of 92 leading energy, transport, industry, and investment companies that advocate and promote a vision for developing a hydrogen economy.

Case study: blue hydrogen and blue ammonia

In September 2020, Saudi Aramco announced its first blue ammonia shipment from Saudi Arabia to Japan (Ewing 2020). This maiden 40-tonne shipment was achieved in partnership with the Institute of Energy Economics Japan and SABIC, supported by the Japanese Ministry of Economy, Trade, and Industry. Shipped blue ammonia was used as a fuel for zero-carbon power generation (Figure 4.5).

The pilot project demonstrated the logistics of converting hydrocarbons to hydrogen and then to ammonia while capturing, utilizing, and sequestering 50 tons of associated CO_2 emissions. Blue ammonia was produced at the Jubail plant of the SABIC-affiliated Saudi Arabian Fertilizer Company in a conventional manner, yielding CO_2 as a by-product. Thirty tons of captured CO_2 was then used to produce methanol at SABIC's Ibn Sina plant. Another 20 tons of the captured CO_2 was transported to the Hawiyah natural gas processing plant, where it was then injected into the pipeline used for enhanced oil recovery at Aramco's Uthmaniyah oil field (Saudi Aramco, IEEJ, SABIC 2020; Shabaneh, Al Suwailem and Roychoudhury 2020). Thus, part of the captured CO_2 was used to produce methanol at Ibn Sina and part was sequestered at Uthmaniyah.

In addition to demonstrating the logistics of the entire blue ammonia value chain, the pilot project showed how CO_2 streams could be tracked and metered within a CCE framework for future commercial applications (Ewing 2020). Understanding the carbon flows of such a pilot batch of blue ammonia helps not only inform the development of an international hydrogen certification scheme but also identify business risks and how to manage them (Brown 2020).

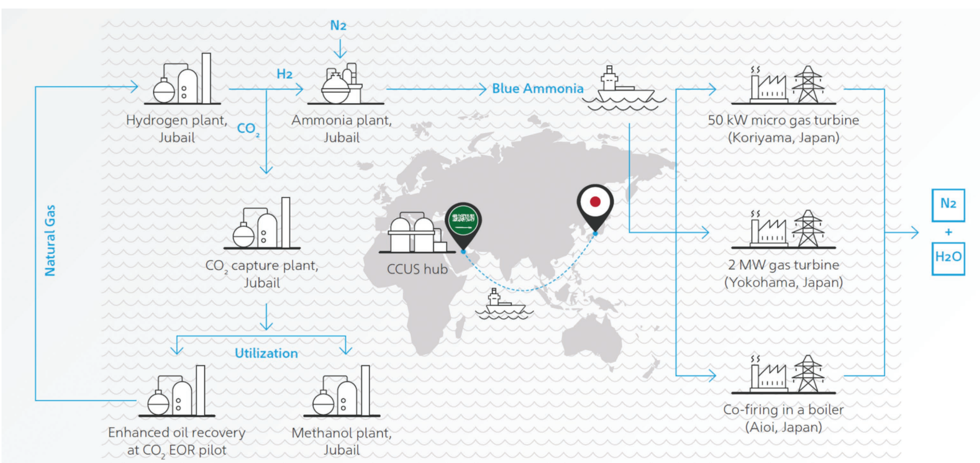

FIGURE 4.5 Schematic of the blue ammonia pilot shipment to Japan.

Source: Aramco (2022).

More recently, in August 2022, the Saudi Aramco Jubail Refinery and SABIC Agri-Nutrients Company's plant in Jubail received the world's first independent certification of blue hydrogen and blue ammonia. The certifications for 8,075 tons and 37,800 tons of product were granted by the German testing agency TÜV Rheinland. To achieve this, a substantial proportion of the CO_2 emissions generated during the manufacturing process must be captured and used in downstream applications (Sabic 2022).

These synergistic CCE achievements associated with blue products leverage the existing infrastructure in successful partnerships between the Kingdom's vital industrial organizations, namely, Aramco and SABIC. They illustrate how to gradually shift the petrochemical industry from fossil fuels to a low-carbon hydrogen economy (KAPSARC 2021).

Conclusion

SABIC has successfully met many of the challenges posed by its approach to sustainability. By collaborating with stakeholders throughout its value chains, it has opened opportunities to create additional value for its products and services. It has shown an inclination to engage with suppliers and customers to transform the links of its existing value chains and gain expertise over the new links it develops. These include those related to CCUS, low-carbon ammonia, and hydrogen.

Hydrogen, which is used as a chemical feedstock and could be explored as a fuel in the future, offers several ways to reduce carbon emissions. This can be achieved either via water electrolysis using renewable energy (green hydrogen) or from conventional SMR but with CO_2 capture and sequestration (blue hydrogen). Therefore, both blue and green hydrogen play crucial roles in decarbonizing SABIC's three carbon-intensive manufacturing processes for methanol, ammonia, and steel. At the same time, the electricity generated from renewables could directly replace conventionally generated electricity.

The short- and long-term technological goals related to hydrogen and electrification support SABIC's carbon neutrality and sustainability commitments. Further, integrating technologies could result in higher resource and energy efficiencies.

With its extensive technical knowledge and commitment toward transitioning to a low-carbon future, SABIC is well placed to become a key player in the future global hydrogen and ammonia markets. Indeed, its sustainable products and solutions could lead to a decarbonized petrochemical industry.

Note

1 For a more detailed understanding of the CCE framework, see www.cceguide.org.

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5

GREEN HYDROGEN IN SAUDI ARABIA'S NEOM

Frank Wouters

Introduction

Countries rarely build economic regions from scratch and such projects are often politically motivated. Examples include the recent projects in Kazakhstan, Brazil, and Nigeria. For instance, Nur–Sultan in Kazakhstan and Brasilia in Brazil are in more central locations than the capital cities they succeeded. Nur–Sultan was meant to be further away from the Chinese border, while Brasilia, Oscar Niemeyer's vision of a future city with stunning architecture, was relocated to central Brazil to be closer to the country's population.

In Saudi Arabia, NEOM is an economic region planned for the northwest of the Kingdom and the centerpiece of Saudi Vision 2030. NEOM, or 'new future', is located north of the Red Sea, east of Egypt (across the Strait of Tiran), and south of Israel and Jordan. NEOM is different from the aforementioned projects in several ways. First, it is not centrally located or intended to replace Riyadh as Saudi Arabia's capital. Second, NEOM's sheer size, at 26,000 km^2 (the size of Belgium), and its unique constitution-like legal framework make it a hybrid between a city and a country. The rest of this chapter refers to NEOM as a region.

NEOM is the vision of a zero-carbon region in that it combines both urban living and nature reserves in a harmonized manner. The region will become the home and workplace of millions of residents from around the world. It will include hyperconnected cognitive communities and cities, ports and enterprise zones, research centers, sports and entertainment venues, and tourist destinations. It is being created to address some of the most pressing challenges facing the world today. These challenges include the impacts of climate change, unrestrained urban development and sprawl, traffic congestion, and environmental degradation. It aims to serve as a model of livability that places people and the planet in harmony, with

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sustainability at its core. NEOM also aims at unmatched livability and economic prospects that will be powered by a profitable economy driven by advanced technology that will pioneer the development of 14 industrial or commercial sectors, including energy. Other sectors are water, food, mobility, manufacturing, design & construction, technology & digital, tourism, financial services, media, health, well-being, and biotechnology. All energy in NEOM will be 100% renewable (predominately from solar and wind), ensuring clean and pollution-free urban environments. NEOM's abundant wind and solar resources will also allow it to produce low-cost green hydrogen.

This chapter first describes NEOM's strategy and the rationale behind its desire to produce green hydrogen. Thereafter, the main potential use cases for hydrogen to be made in NEOM are explained. NEOM's hydrogen research strategy and its green hydrogen program, including the NEOM Green Hydrogen Company (NGHC), are then described. The chapter ends with conclusions.

NEOM's energy strategy

NEOM is pursuing a zero-carbon philosophy for its energy system, which will be based on solar and wind power. NEOM's location is an important factor in this respect. The region's solar and wind resources are abundant and complementary. The wind is predominantly of thermal origin over the Red Sea and flows through the Gulf of Aqaba. In combination with the setting sun, it provides an exceptionally high annual load factor that is anticipated to be up to 70%. Solar and wind power can thus cover a large part of NEOM's energy demand through direct electrification, albeit not 100%.

The cost of green hydrogen produced in NEOM, assuming current electrolyzer and green electricity costs, is expected to be below $2/kg, among the lowest in the world. If the costs of green electricity and electrolyzers continue to fall, so will the production cost of green hydrogen. Saudi Arabia is blessed with not only low-cost hydrocarbons but also sustainable energy sources, guaranteeing a firm position in any future energy market. Figure 5.1 compares renewable electricity generation costs globally.

Saudi Arabia has one of the lowest costs of renewables globally, which will contribute to lower decarbonization costs across the Kingdom. NEOM can provide renewable and clean energy to produce (low-carbon) chemicals, steel, aluminum, fertilizers, and mining at an industrial scale. Within the region, hydrogen and its derivatives can be used to stabilize the electricity system as well as store energy and dispatch power. It can also serve as a fuel for, say, road and marine transport.

In addition to the potential for hydrogen use in domestic and regional markets, it can be exported. This is the focus of NEOM's green hydrogen production. NEOM is geographically located between Europe and Japan/Korea, which are the

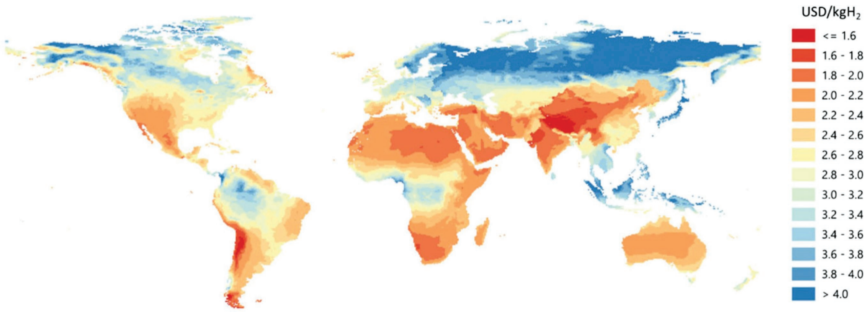

FIGURE 5.1 Long-term hydrogen costs from hybrid solar photovoltaic and onshore wind systems.

Source: IEA (2019).

Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city, or area. Electrolyzer CAPEX = $450/kWe, efficiency (LHV) = 74%; solar photovoltaic CAPEX and onshore wind CAPEX = $400–1000/kW and $900–2500/kW depending on the region; discount rate = 8%.

TABLE 5.1 Hydrogen shipping costs as a function of distance to NEOM from various parts of the world

	Distance to NEOM (km)	*Shipping cost ($/kg)*
EU	8,200	0.62
Korea	15,200	1.28
Japan	15,600	1.33

Source: HySupply Shipping Analysis Tool v1.1.

two main import markets for hydrogen and hydrogen products. Since the cost of shipping a commodity is a function of the distance, shipping to Japan is more than twice as expensive as shipping to Europe. Table 5.1 shows the cost differences.

Achieving NEOM's ambitious plan to become a global center of a thriving knowledge- and innovation-based economy will not be straightforward given the lack of infrastructure and human capital. NEOM will be funded initially by Saudi Arabia's sovereign wealth fund, namely, the Public Investment Fund. However, attracting adequate foreign direct investment in the long run will be crucial. Innovation is the foundation on which NEOM will be built, stretching from infrastructure, manufacturing, education, energy, food, water to healthcare, and life sciences. For people and companies to innovate in NEOM, economic ecosystems across sectors must be created, which will take time to develop. How this chicken-and-egg conundrum will be solved is one of the crucial puzzles for NEOM. It will be addressed by integrating sectors' strategies and developing NEOM's manufacturing center. For example, people, industries, and technology will come together in

NEOM's industrial city OXAGON to function in harmony with nature. Hence, the state-of-the-art approaches of Industry 4.0 and the circular economy will merge to create factories of the manufacturing products of the future. In OXAGON, not only can innovators and entrepreneurs accelerate ideas from labs to market but people can also come together to live, work, and play in thriving communities.

Green hydrogen applications in NEOM

With excellent renewable resources, abundant low-cost land, and favorable legislation, NEOM will possess all the assets to become a world-class low-cost hydrogen producer. The hydrogen produced will be used domestically (i.e., in NEOM and Saudi Arabia at large) as well as be exported. Several possible applications are being explored, as described in the following subsections.[1]

Balancing the electricity system

In NEOM's electricity system dominated by (variable) renewables, storage and dispatchable generation are required to guarantee a reliable energy supply. While demand-side management and batteries can provide short-term storage, hydrogen is required for longer-term storage. Hydrogen can be stored inexpensively and reconverted to electricity using fuel cells and gas turbines when demand is above the immediate supply from solar and wind sources. Since NEOM's electricity system is projected to run on 100% renewable energy, hydrogen is required to stabilize the system and provide a reliable supply. The need for hydrogen in an electricity system increases as the variable renewable energy share rises (Figure 5.2). Above a certain threshold, building additional renewable capacity would be inefficient without long-term storage alternatives. A higher share of renewables could become feasible by providing seasonal storage, for example via hydrogen.

Hydrogen for road transport

Hydrogen is a versatile fuel that can be converted in a fuel cell to power an electric vehicle. One of hydrogen's strengths is in long-haul, heavy-duty transport. Hyzon Motors is a leading global supplier of zero-emission hydrogen fuel cell-powered commercial vehicles. In April 2021, it signed a memorandum of understanding with NEOM to develop a heavy-duty commercial vehicle assembly facility (Hyzon Motors 2021). The development project will be run jointly with Modern Group, a Saudi industrial conglomerate. The anticipated annual capacity of this new regional assembly facility is up to 10,000 vehicles for distribution across Saudi Arabia and the Gulf region (Figure 5.3).

Traveling in NEOM may not require individual car ownership, as there will be plenty of autonomous mobility options and rail or mobility-as-a-service options. A variety of mass transport options are nonetheless required, including from

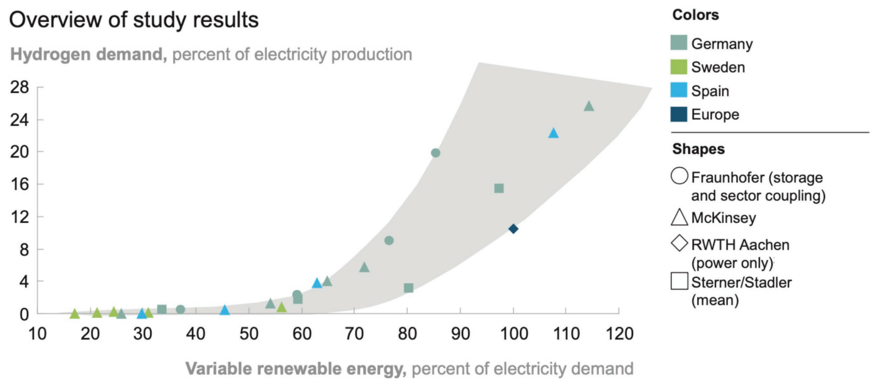

FIGURE 5.2 The rising need for hydrogen as the variable renewable energy share increases.

Source: Hydrogen Council (2017).

Notes: Based on figures from the Fraunhofer Institute for Solar Energy Systems ISE (2017), BMW, RWTH Aachen, Sterner and Stadler (2014), and McKinsey. (1) Least-cost modeling to achieve the 2°C scenario in Germany by 2050 in an hour-by-hour simulation of power generation and demand; assumptions: no regional distribution issues (would increase the hydrogen pathway) and no change in energy imports and exports. (2) Simulation of storage requirements for a 100% renewable energy share in Europe; only power-sector storage considered (lower bound for the hydrogen pathway).

FIGURE 5.3 Hyzon vehicle designs and fuel cells.

Source: Hyzon Motors (2021).

the planned NEOM International Airport to residential areas or regions bordering NEOM. For this, Hyzon and NEOM are working on a concept for deploying hydrogen buses, including hydrogen refueling stations.

Off-grid energy supply

NEOM is aiming to preserve 95% of its land for nature. To cater to the millions of tourists it aims to attract annually, dedicated off-grid camping sites will be constructed in harmony with the natural environment. The supply of power and other utilities to such remote sites demands specific solutions. Traditionally, such sites are powered by diesel generators, but this is not an option for NEOM. A combination of onsite renewable energy and batteries can cover much of the electricity demand. However, hydrogen converted in a fuel cell takes up less space while also generating heat and water along with electricity.

E-fuels

Several e-fuels are promising for NEOM, including ammonia, methanol, and more complex hydrocarbons. E-fuels are synthetic fuels resulting from the combination of green (or e-hydrogen) gas and CO_2 captured either from a concentrated source (e.g., flue gases from an industrial site) or nitrogen or CO_2 from the air via direct air capture. NEOM's Hydrogen Innovation and Development Center (HIDC) is continuing its development of production, conversion, and end-use technologies.

Ammonia

Ammonia is commonly produced from hydrogen and nitrogen using the Haber–Bosch process, following the ammonia synthesis reaction:

$$\mathbf{3H_2 + N_2 \rightarrow 2NH_3}$$

The hydrogen at NEOM will be produced in a water electrolyzer using a combination of solar and wind electricity, whereas the nitrogen is produced in an air separation unit, also powered by green electricity. A small ammonia loop, producing approximately 50 tons per day, could run on a 40-MW electrolyzer and used to produce ammonia for use in NEOM and elsewhere in Saudi Arabia as well as for export.[2]

Catalysts are important elements to increase the efficiency of the Haber–Bosch process as well as decompose ammonia. NEOM is exploring ways to cooperate with the King Abdullah University of Science and Technology (KAUST) on developing advanced processes. Such processes include the development and use of the catalytic conversion of ammonia to nitrogen and hydrogen. Ammonia is quickly emerging as a major transport vector for hydrogen as well as developing into an energy vector (e.g., as a marine fuel or co-fired with coal in power plants). However, most future demand will be for pure hydrogen (e.g., for use in fuel cells). Hence, the ability to crack ammonia back into its components will be a crucial step in the value chain. KAUST and NEOM could cooperate, together with industrial partners, on developing catalysts that increase the efficiency of the ammonia cracking process. These partners could, for example, build on KAUST's work using advanced catalysts based on ruthenium, potassium, and calcium oxide for decomposing ammonia.

Methanol

Methanol, also known as methyl alcohol among other names, is the simplest alcohol, with the formula CH_3OH (a methyl group linked to a hydroxyl group, often abbreviated to MeOH). It is a light, volatile, colorless, flammable liquid with an alcoholic odor such as that of ethanol (potable alcohol). Methanol is a widely adopted chemical that can be used to produce synthetic gasoline, olefins, polypropylene, methyl tertiary-butyl ether, formaldehyde, and solvents. These products are used in industries such as automotive, construction, electronics, solvents, pharmaceuticals, appliances, packaging, and insulation because of its unique properties. It significantly reduces emissions of sulfur oxides, nitrogen oxides, and particulate matter. Methanol can also be used directly as a fuel. For example, it can be highly efficient for use in marine diesel engines. Since a methanol spill at sea does not have the adverse effects of other marine fuels, methanol could be stored in the double hull of modern vessels unlike ammonia and diesel. The automotive segment led the methanol market in 2019, accounting for a 24.8% share in terms of value. The global methanol market is projected to reach $26.7 billion by 2025, rising at a compound annual growth rate of 5.5% between 2020 and 2025 (Research and Markets 2021).

Since methanol is produced through the hydrogenation of CO or CO_2, it could also be used to capture and recycle CO_2 emissions (Figure 5.4):

$$\mathbf{CO + 2H_2 \rightarrow CH_3OH}$$

$$\mathbf{CO_2 + 3H_2 \rightarrow CH_3OH + H_2O}$$

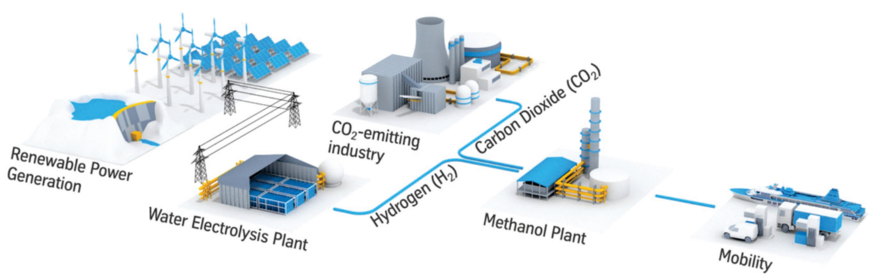

FIGURE 5.4 Small methanol production set-up.

Source: Thyssenkrupp (2022).

NEOM's hydrogen comes from water electrolysis. Since there are no refineries, fossil fuel-driven power plants, or other industrial sources of carbon, its carbon would either be biogenic or captured from air. NEOM is exploring the latter option, called direct air capture.

Use as a feedstock in Saudi Arabian industry

The key uses of hydrogen in Saudi Arabia are refining and producing ammonia (Qamar Energy 2020). First, hydrogen produced through steam methane reforming is used in Aramco's refineries, with production facilities in Yasref, Luberef, Rabigh, and Jeddah and a new unit being developed in Jubail. Total production capacity from these units is 616,000 tons of hydrogen per year, with an additional 150,000 tons per year planned when Jubail comes online in 2023. Second, the Kingdom produced about 4.3 million tons of ammonia in 2021, requiring 774,000 tons of hydrogen per year (Statista 2022). Hence, domestic demand for hydrogen in refining and producing ammonia amounts to around 1.7 million tons per year. This number indicates that the domestic market is already seven times larger than the planned hydrogen production capacity at NEOM. The methanol production at Ar Razi and Sipchem has a combined capacity of 6 million tons per year. If this is converted from natural gas as a feedstock to hydrogen with captured CO_2, domestic demand would require an additional 750,000 tons of hydrogen.

Export

As mentioned in the Introduction, predictions of global hydrogen demand vary wildly. This is partly because hydrogen is only produced in captive installations to produce selected chemicals, mostly fertilizers, and for refining. Crucially, future hydrogen demand must develop and grow substantially. However, hydrogen is recognized by governments and stakeholders globally as a substantial element in the energy mix of a net-zero emissions future. Many countries, including European Union (EU) member states, Korea, and Japan, require hydrogen but lack the potential for sufficient domestic production. These areas are potential offtake markets for Saudi hydrogen.

To cover its future need for renewable hydrogen, Europe is likely to rely on imports. According to the EU's REPowerEU strategy presented in March 2022, the Hydrogen Accelerator initiative increased the hydrogen to be consumed in the EU in 2030 to 20 million tons per year, up from 5 million tons. Half that (10 million tons) will need to be imported, mostly from neighboring North Africa and Ukraine, but also from the Gulf region. If one-third of future imported hydrogen came from the Gulf, this would constitute 3.5 million tons, a business opportunity valued at $7–10 billion annually. While this is below the trade volume of fossil fuels imported into Europe from Gulf countries ($32 billion in 2019), the expected hydrogen trade volume is a conservative estimate, with significant upward potential

(European Commission 2022). The Belgian Hydrogen Import Coalition (Port of Antwerp 2021), for example, estimates that 7,000 TWh of energy will be imported into the EU annually by 2050. This would place hydrogen trade from the Gulf into the EU comparable to today's liquefied natural gas volume.

One interesting idea is to connect Europe to Saudi Arabia via a hydrogen pipeline (IEF 2021). Although no concrete plans yet exist, a potential route could connect Saudi Arabia through Egypt with the European gas grid. Europe is examining the conversion of its extensive natural gas pipeline system to accommodate hydrogen, with several backbone projects being studied (Guidehouse 2020). If natural gas pipelines in the Middle East are also converted from natural gas to hydrogen, a connection to the Arab Gas Pipeline or planned EastMed Pipeline could be considered (see Chapter 8).

Bunkering

Ammonia has long been considered one of the most promising alternative marine fuels to reduce greenhouse gas emissions in the shipping industry. This is because it does not emit CO_2 when combusted. This is in line with the International Maritime Organization's strategy to reduce CO_2 emissions by 2050 (IMO 2021). Green ammonia holds great potential, as it is produced from renewable electricity, water, and air with no CO_2 emissions. Several manufacturers of marine engines, including Wärtsilä and MAN, are developing dual-fuel engines that can run on ammonia (Wärtsilä 2020). Approximately 12% of the world's trade flows through the Red Sea and marine shipping accounts for 80% of the world's trade in goods. Thus, NEOM is strategically located to supply the marine transport industry with green ammonia (MFAT 2021).

Yachting

Together with Amaala and the Red Sea Project, NEOM is part of the Red Sea Collection being developed by the Public Investment Fund. One of the aims of the initiative is to develop sustainable yachting in the Red Sea in harmony with the delicate marine environment. Hydrogen and hydrogen-derived fuels such as methanol and ammonia are proposed as clean marine fuels for the area, as they would not affect the unique coral reef ecosystems along the Red Sea's coastline. There are a reported 365 scleractinian reef-building coral species in the Red Sea, including 19 endemic species (Fine et al. 2019).

NEOM's hydrogen research strategies

In addition to serving international and domestic markets with hydrogen, NEOM strives to be a technology development hub for innovative applications and technologies in the hydrogen domain. Part of NEOM's hydrogen strategy is to build its HIDC around one or two 20 MW electrolyzer units supplied by thyssenkrupp. The electrolyzer units will be identical to those at the heart of the green hydrogen project, dubbed the NGHC, between Air Products, ACWA Power, and NEOM. The NGHC consists of 2.2-GW electrolyzer capacity combined with a 4,000-ton-per-day ammonia loop. The HIDC has two main aims. The first aim is to advance practical knowledge of the 20-MW electrolyzer and provide a platform for electrolyzer R&D. The second aim is to develop e-fuels such as methanol and jet or marine fuel, potentially in combination with innovations such as direct air capture and advanced CO_2 capture technologies.

The 20-MW alkaline electrolyzer units of NEOM's HIDC will be supplied by thyssenkrupp. The heart of the electrolyzer unit is the stack, consisting of a range of cells. Figure 5.5 shows the principle of a cell in an alkaline electrolyzer stack. The electrodes are nickel-coated stainless steel; the diaphragm or separator consists of zirconium dioxide stabilized with solid electrolyte polyphenylene sulfide mesh.

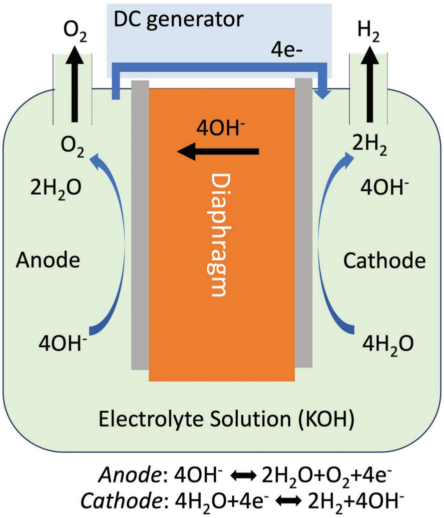

FIGURE 5.5 The principle of an alkaline electrolyzer cell.

Source: Author.

The ionic charge carrier is the hydroxyl ion OH-, with KOH and water permeating the porous structure of the diaphragm. Although unwanted, some of the produced hydrogen and oxygen dissolved in the electrolyte pass through the diaphragm, limiting the lower power-operating range and ability to operate at higher pressure levels. To prevent this, thicker diaphragms are used; however, this creates higher resistance, drastically reducing current density at a given voltage and lowering efficiency. NEOM is planning to work with thyssenkrupp on increasing the current density and raising efficiency. The focus on advanced designs could include zero-gap electrodes, thinner diaphragms, and different electrocatalyst concepts.

Thus, NEOM aims to become a hub for research and innovation in hydrogen developments, linking industrial actors with applied research organizations such as KAUST. These could encompass novel hydrogen storage solutions, fuel cells, electrolyzers, and components. Alternatively, it could include the production of more complex fuels such as synthetic kerosine, for which direct air capture could be applied. However, NEOM could also work to reduce the cost of electrolyzers by becoming a manufacturing hub either for them or for certain components.

NEOM's abundant low-cost clean energy will enable water to be produced from seawater cost effectively. The brine will not be discharged and rather, valuable minerals will be extracted. Indeed, the availability of abundant low-cost energy could be an inducement for energy-intensive industries to relocate (Gielen et al. 2021). Abundant clean water will be used in sustainable food production and enable the production of green fuels.

Case study: NEOM's green hydrogen company

In July 2020, a consortium including NEOM, Air Products, and ACWA Power announced the launch of the NGHC (Parnell 2020). The project, equally owned by the three partners, will integrate 4 GW of renewable power from solar, wind, and storage. It also aims at producing 600 tons a day of green hydrogen by electrolysis, nitrogen by air separation, which translates into 1.2 million tons of green ammonia annually. The project is scheduled to go onstream in 2026. Air Products will distribute ammonia to global markets where they will dissociate it back to hydrogen for sale primarily focused into the transportation sector (Figure 5.6).

Thyssenkrupp will provide the electrolyzers, Air Products will supply the air separation unit, and Haldor Topsoe will supply the ammonia synthesis unit. ACWA Power leads the development phase of the renewable energy part of the project, with Air Products leading the development phase of the green hydrogen part of the

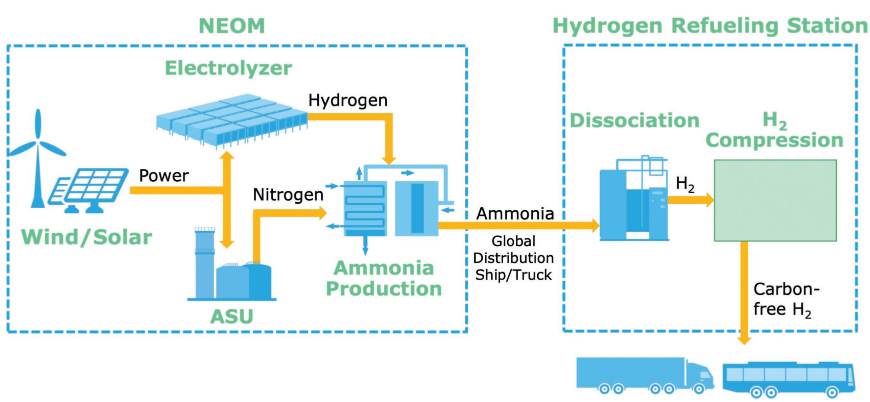

FIGURE 5.6 Schematic overview of the NEOM green hydrogen project.

Source: Air Products (2020).

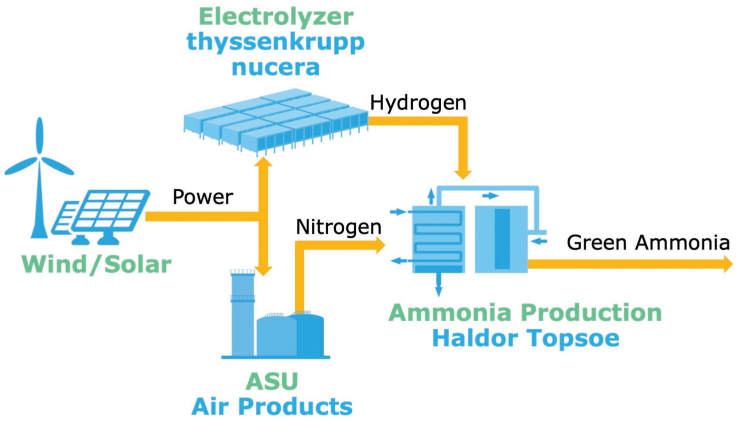

FIGURE 5.7 Technology providers and partners in NEOM's green hydrogen project.

Source: Air Products (2020).

project and overall system integration. Finally, Air Products assumed the responsibility for the engineering, procurement, and construction of the overall project (Figure 5.7).

A 1.2-million-ton-per-year ammonia project is large, but not unusual, with most modern ammonia projects in the million tons range. The Gulf Coast Ammonia project that is under construction in Texas has a similar capacity of anhydrous ammonia per year (1.3 million tons). Air Products is also involved in that project, supplying hydrogen from a steam methane reforming unit and nitrogen from an air separation unit. The NGHC will significantly contribute to the development of the global hydrogen economy. Air Products' investment, both in NEOM and in its sales and distribution network to deliver the manufactured product, is impressive. Beyond the overall $8.4 billion overall investment cost, it will invest an additional $2 billion in distribution to end customers. Building this plant will therefore impact the cost of electrolyzers and ammonia crackers significantly. The cost of initial infrastructure to deliver this volume of ammonia might be significant, but those volumes can later be expanded at far lower incremental delivery costs.

Conclusion

NEOM aims to be a new model for livability, where people enjoy a high quality of life in harmony with the natural environment and break the trend of unsustainable urban living. In terms of energy, whether used for life, industry, transport, or water and food production, NEOM will be carbon-free or carbon-negative. In other words, it aims to capture more carbon from the atmosphere than it emits. NEOM's location provides for excellent solar and wind power electricity with a world-class combined load factor. That electricity can be firmed up with hydrogen as storage in addition to batteries and used to produce hydrogen and hydrogen-based fuels cheaply. NEOM seeks to become a hub for innovation and human progress and the activities around the energy–water–fuel nexus are at the intersection of science and business. The best available technologies for sea mining, direct air capture, and fuel production, among others, can be piloted at NEOM's HIDC. They can be scaled up to industrial-scale production facilities such as the NGHC. NEOM will also be a hub for manufacturing, deepening the Saudi-based value chain in an inclusive manner. Partnerships with thyssenkrupp, Hyzon Motors, Air Products, and others will drive technology development at NEOM, from the prototype stage to demonstration, early adoption, and maturity. In summary, the Kingdom has been a reliable supplier of fossil energy to global markets for decades. Now, with NEOM at the core of developing zero-carbon fuels, Saudi Arabia is in a prime position to become an important clean energy supplier.

Notes

1 This list is a snapshot and not all these options may eventually materialize. Additional opportunities may also arise over time.
2 thyssenkrupp, one of NEOM's suppliers, has designed such an installation at this scale.

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6

GLOBAL LANDSCAPE OF RESEARCH, DEVELOPMENT, DEMONSTRATION, AND INNOVATION IN HYDROGEN TECHNOLOGY

Learnings for Saudi Arabia

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Introduction

A country's competitive position in the global hydrogen economy is defined by its ability not only to produce and transport a kilogram of clean hydrogen at a highly competitive price but also to innovate in hydrogen technologies throughout the value chain. This hydrogen sector is predicted to become a trillion-dollar commodity market by 2050 in a carbon-constrained world (Bloomberg New Energy Finance 2020; Hydrogen Council 2020). Saudi Arabia shows promise in its ability to cheaply produce clean hydrogen. However, it is ill-equipped for capturing value in the end-use part of the hydrogen value chain, which requires substantial effort and targeted investment in research, development, demonstration, and innovation (RDDI) ecosystems. Delving into a complex and broad ranging topic such as RDDI in hydrogen technologies is highly challenging due to the lack of available information at many levels. Hence, we use the data available from global sources on funding, technology readiness levels (TRLs), patenting, innovation ecosystems, and so on to address the main subject matter of this chapter.

Clean hydrogen technologies comprise a subset of a vast array of loosely defined, synergetic, overlapping clean climate technologies. Climate technologies, which are also called low-carbon and clean energy technologies, mitigate climate change by limiting greenhouse gas emissions and adapting to their adverse effects (United Nations Framework Convention on Climate Change 2017). Some examples of climate technologies include wind/solar power; carbon capture, utilization, and storage (CCUS); batteries; and smart grids.

IEA (2020a) states that up to 35% of emission reductions for achieving the climate goals in the Paris Agreement are contingent on technologies that are presently

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in the large prototype or demonstration stage. Therefore, accelerating innovation driven by research and development (R&D) and rapidly adapting clean energy technologies are at the heart of the energy transition (Meckling et al. 2022). Historically, energy innovation has depended on public R&D spending and institutions that catalyze private R&D spending, including venture capital.[1] Given the enormity of the task of achieving the Paris goals, funding and institutions need drastic transformation (Meckling et al. 2022). Moreover, efficient research translation models are necessary to quickly adapt research from laboratories to industries (or low levels of development to market-ready applications) and close the innovation cycle. Hydrogen technologies constitute a significant part of the clean energy technology palette. Hence, focused funding and institutional development are indispensable for hydrogen, although innovation ecosystem transformation is mostly technology-agnostic.

The cost of delivered hydrogen is one of the most critical drivers of hydrogen technology innovation. A global initiative in which Saudi Arabia is a member, Mission Innovation 2.0's Clean Hydrogen Mission (Carbon Trust 2021), has identified the need to reduce the cost of clean hydrogen to $2/kg by 2030. This is seen as the tipping point to drive economies of scale and offer a commercially viable alternative to fossil fuels. The end-user cost includes production, storage, and distribution costs. Although storage and transportation are essential, production costs are the highest. Innovation could reduce production costs by 60% from 2021 levels by 2030. Natural gas reforming with carbon, capture, and storage (CCS) and renewable electrolysis is the most often-used technology that requires further R&D and innovation to reduce costs (Carbon Trust 2021). In this chapter, we examine the other crucial drivers of innovation besides cost.

We identify four broad steps for achieving RDDI goals to support the hydrogen economy in Saudi Arabia (see Figure 6.1). Step 1 identifies the national priorities and

FIGURE 6.1 Four steps toward the hydrogen economy in Saudi Arabia.

Source: Authors, based on information from King Abdullah University of Science and Technology (KAUST).

international commitments and is adequately discussed in Chapters 1 and 2. Step 2 quantifies the role of hydrogen in addressing Saudi Arabia's goals and priorities, which is contingent on the constraints on natural resources, legacy of the oil and gas economy, and prevailing policy climate. The hydrogen strategy and industrial infrastructural path can thus be broadly based on the considerations listed in Steps 1 and 2.

This chapter discusses the hydrogen R&D areas and technology roadmap required for Saudi Arabia (Step 3) and the Kingdom's innovation ecosystem needs (Step 4) and is structured as follows. The first part of the chapter analyzes the status of global RDDI in terms of the TRLs, funding, scale up, and commercialization (pilots and demonstration) of technologies crucial for advancing the hydrogen economy worldwide. The aim of this analysis is to appraise international developments in the hydrogen technology field and consider relevant learnings for Saudi Arabia. The TRLs of various technologies in the hydrogen value chain are discussed; this also includes a brief overview of the progress of hydrogen RDDI globally, including research and patent development. Based on the recommendations from the technology chapters of this book, technologies crucial for the hydrogen value chain in Saudi Arabia are then selected and a roadmap for RDDI is recommended.

A key argument made here is that not all technologies required for the Kingdom need RDDI. Hence, we categorize technologies needing:

1 Basic research and technology translation,
2 Corporate or firm research,
3 Technology acquisition, and
4 Technology licensing.

Local and international academic institutions and industries can collaborate to realize the potential application of climate technology solutions across all four categories.

The second part of the chapter focuses on identifying the ecosystem needed to carry out the required RDDI and industrial deployment of relevant technologies at scale in Saudi Arabia. The main message of this part is that the current Saudi research and innovation infrastructure (i.e., institutions and human capital) cannot compete with major economies that are highly innovative in science and technology (S&T). A key lesson drawn from this chapter is that building an innovative and dynamic RDDI ecosystem made in Saudi Arabia will be crucial for allowing the required large-scale penetration of hydrogen technologies. Such an ecosystem would be technology-agnostic and valuable for furthering other fields of S&T. King Abdullah University of Science and Technology's (KAUST's) knowledge exchange model (KEM) framework that translates university research into economic goals is suggested as a practical and pragmatic approach for meeting Saudi Arabia's innovation objectives. The chapter argues that the KEM is indispensable for politicians, policymakers, and research funders seeking to translate university research into public benefit more efficiently and effectively. Moreover, it can further not only the case of the hydrogen economy but also all research endeavors carrying national and global importance for the Kingdom.

RDDI in clean energy and hydrogen technologies: current status

RDDI funding and supportive policies are critical determinants of clean energy innovation, as they reduce costs over time, from lab-scale research (prototype to pre-competitive and competitive with incumbents) to the market-ready stage (see Figure 6.2). While tax incentives and carbon pricing are crucial for large-scale commercial deployment, policies supporting adequate R&D spending are fundamental (Roberts 2020). Funding sources can be diverse and depend on the maturity level of the technology. Generally, RDDI investments occur through three primary routes: public funding, industrial or private sector participation, and the infusion of venture capital. As Figure 6.3 underlines, resource scarcity, called 'the valley of death' (for new ideas), is not due to monetary constraints. Rather, it is caused by the lack of efficient interaction among researchers, financiers, and entrepreneurs, who

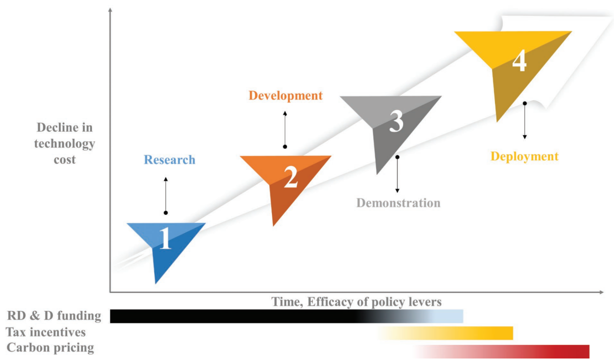


FIGURE 6.2 Role of policy levers in enhancing clean energy innovation across stages. Light shading means low effectiveness and dark shading means high effectiveness.

Source: National Science Foundation (2012).

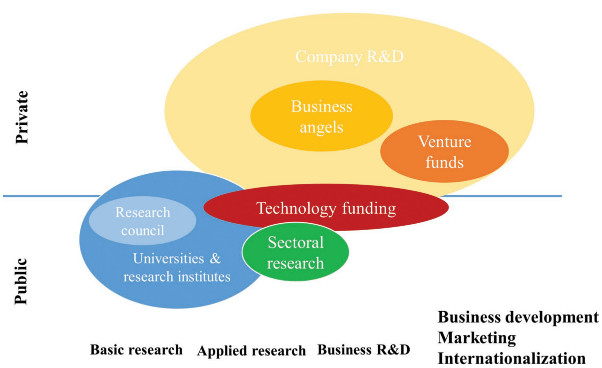


FIGURE 6.3 Research and innovation funding system.

Source: Adapted from Nagano (2005); Bizri (2018).

must use their highly divergent competencies to combine ideas to advance in that space (Bizri 2013; Nagano 2005). Recognizing this gap, we discuss this interface in this chapter, including technology translation (see the KEM on page 28). The valley of death can also appear in the deployment stage of the innovative technology path. Deployment incorporates business models and competitiveness, supply chain management, human capacity building, policy readiness, finance, and public acceptance; hence, it is vulnerable to weak links in the aforementioned areas.

Global RDDI funding

Hydrogen R&D spending must be a global effort with intense international cooperation and large-scale technology sharing to avoid the pitfalls and enable low-cost, widely affordable technologies. Similar to projections of hydrogen demand in final demand scenarios up to 2050, there is great uncertainty about the investment in R&D along the hydrogen value chain needed to achieve global decarbonization goals. Many countries are still formulating their national hydrogen goals; yet, their existing R&D infrastructure is largely ill-equipped to deliver on these.

A study by the European Parliament Committee on Industry, Research and Energy (ITRE) projects that $180–470 billion in research and infrastructure in the hydrogen value chain is needed to achieve the EU's REPowerEU 20 Mt of hydrogen production and demand target. The ITRE study spells out the importance of supporting the required R&D by implementing demonstration at an industrial scale, strengthening the role of small and medium enterprises (SMEs), and improving workers' education and skills as the three key enabling factors. The role of public/private partnerships, EU-wide funding agencies, and strong international cooperation in technology development and sharing is highlighted. Another global organization, the International Energy Agency (IEA), states that nearly $90 billion of public funding is needed by 2026 to support R&D and demonstrations of critical technologies for achieving net-zero by 2050. Roughly half of this sum is required for making hydrogen technologies market-ready (IEA 2022a).

Furthermore, Steven Chu, an influential voice in energy transition, a Nobel laureate, and a former US Secretary of Energy under the Obama administration, has advocated for the reinvestment of 10% of revenue in R&D in high-tech industries (Chu 2009; Hatzichronoglou 1997). Considering that the Hydrogen Council predicts the global revenue from hydrogen to exceed $2.5 trillion by 2050 (Hydrogen Council 2017), 10% would be in excess of $250 billion annually, a spending level that the world should reach progressively by 2050. However, the world is far from spending this amount on RDDI development in the clean energy sector, including hydrogen. Annual investment in this sector totaled $2.2 trillion in 2021 and has been steady since 2016 (see Figure 6.4). Further, while government spending on R&D has increased to $38 billion over the same period, it only constitutes 1.7% of the total clean energy investment as estimated by the authors (Mission Innovation 2020).

These funding projections by the EU and the IEA or based on the recommendations by Chu underline several points. The first is the vast amount of public and

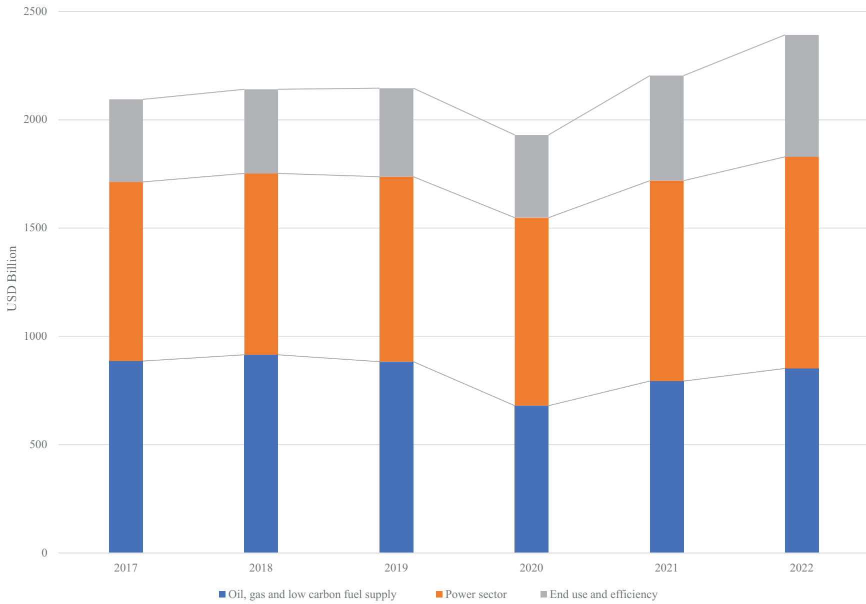


FIGURE 6.4 Global energy investment, 2017–2022. Here, the energy infrastructure includes the midstream and downstream oil and gas infrastructure, electricity networks, and batteries. Investment is measured as the ongoing capital spending in energy supply capacity (fuel production, power generation, and energy infrastructure) and the energy end-use and efficiency sectors (buildings, transport, and industry).

Source: Adapted from IEA (2022b); World Energy Investment 2022, https://www.iea.org/data-and-statistics/charts/global-energy-investment-2017-2022, IEA license CC by 4.0.

private money required to establish the R&D fundamentals of a thriving global hydrogen economy. Second, no single country can achieve any of these goals alone, making global cooperation in R&D and technology sharing paramount. Third, the amount of R&D funding needed is unclear.

This chapter therefore asks and answers the following questions:

- How much funding directly supports hydrogen technologies and through which channels?
- Which countries have taken the lead in this field and could be called early movers?

This information could help decipher current and required investments in hydrogen R&D and country-specific spending targets. All this analysis is pertinent to understand Saudi Arabia's required future investment in RDDI to secure a viable hydrogen economy. The division of R&D investments from public funding, industrial or private sector participation, and the infusion of venture capital is challenging to find or unavailable for many countries. Hence, below, we provide a snapshot of the hydrogen funding data from available sources and make recommendations.

Public R&D

A total of \$38 billion in public energy R&D was spent in 2021, of which \$25 billion was spent on low-carbon or clean energy technologies such as energy efficiency, CCS, renewables, hydrogen, energy storage, and nuclear and smart grids (IEA 2022c). A significant proportion aimed to enhance nuclear energy and energy efficiency. Much of the funding was spent on projects in the final stages of demonstration that were to be commissioned in 2023–2024. The division of publicly funded R&D in specific technologies is unavailable for 2021. However, these data are available from the IEA (2020a) report, which shows hydrogen funding within the low-carbon R&D budget. Figure 6.5 shows that \$17 billion was provided through public financing for all low-carbon R&D globally, with 8% of this amount allocated to funding for hydrogen technologies (approximately \$1.4 billion).

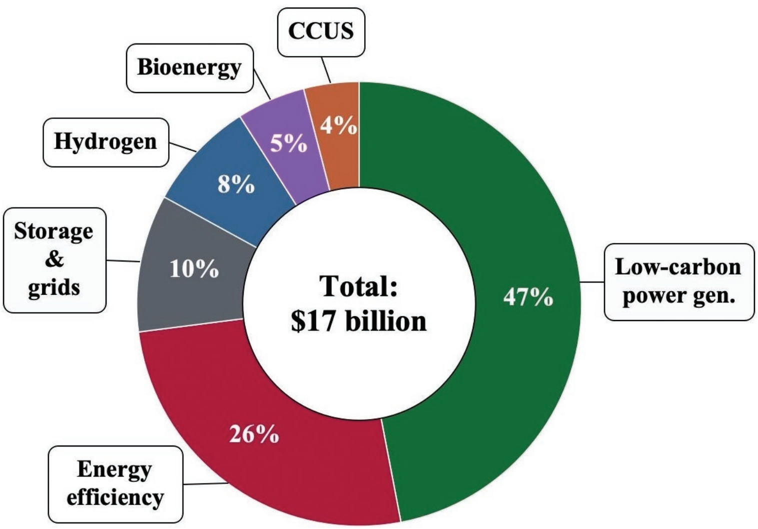


FIGURE 6.5 Global publicly financed low-carbon R&D allocated to specific technology areas, 2019. These data include the generation, storage, transportation, and end use of hydrogen within the ambit of hydrogen technologies. Several energy-saving and emission reduction technologies (CCUS, high-pressure liquid and gas storage) are integral to this range of hydrogen technologies.

Source: Adapted from IEA (2020a), Global public low-carbon energy R&D allocated to specific technology areas, 2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-public-low-carbon-energy-r-and-d-allocated-to-specific-technology-areas-2019, IEA license CC by 4.0.

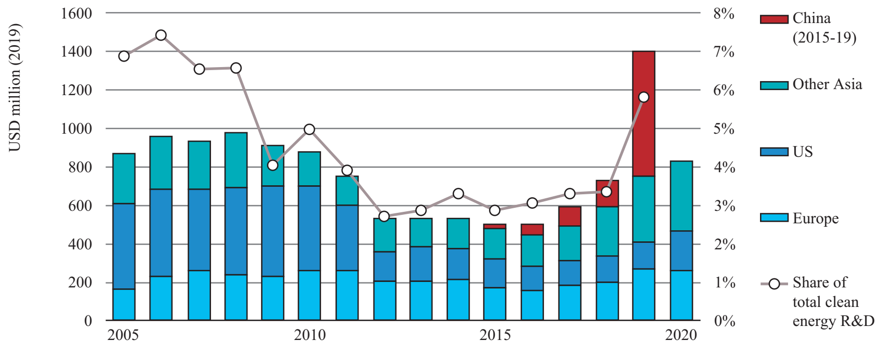


FIGURE 6.6 R&D spending on hydrogen technologies, 2005–2020. Europe includes Germany and France, while 2020 data for China are unavailable.

Source: IEA (2021), Global Hydrogen Review 2021, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2021, License CC by 4.0.

Figure 6.6 shows the regional division of publicly funded R&D investment in hydrogen-related technologies from 2005 to 2020. Only a few countries invested in hydrogen R&D, and China and the United States are world leaders in R&D in hydrogen technologies by a large margin. Over recent decades, Japan and South Korea have made significant investments in hydrogen technologies, followed by Germany, France, and other European countries. The share of R&D in the EU has consistently increased. In particular, the need to accelerate energy independence from oil and gas has intensified since the energy crisis precipitated by the Ukraine/Russia conflict. Yet, the overall message is that public R&D funding in hydrogen and related technologies is lagging behind national ambitions. Further, it is characterized by substantial regional differences and constitutes only a fraction of overall spending on clean energy.

Private R&D

Ideally, public expenditure needs to incentivize private investment in crucial climate technologies since R&D investment from the private sector has a multiplier effect. IEA (2022b) reports that the private sector funded approximately $117 billion in firm-financed R&D in 2021 (see Figure 6.7). The share of the oil, gas, and automotive sectors was the largest ($70 billion). While batteries, hydrogen, and energy storage only accounted for approximately $2 billion, an encouraging observation is that their share of total revenue was the highest, nearing 5%. R&D in renewable energy ($10 billion) also supports the development of the hydrogen infrastructure.

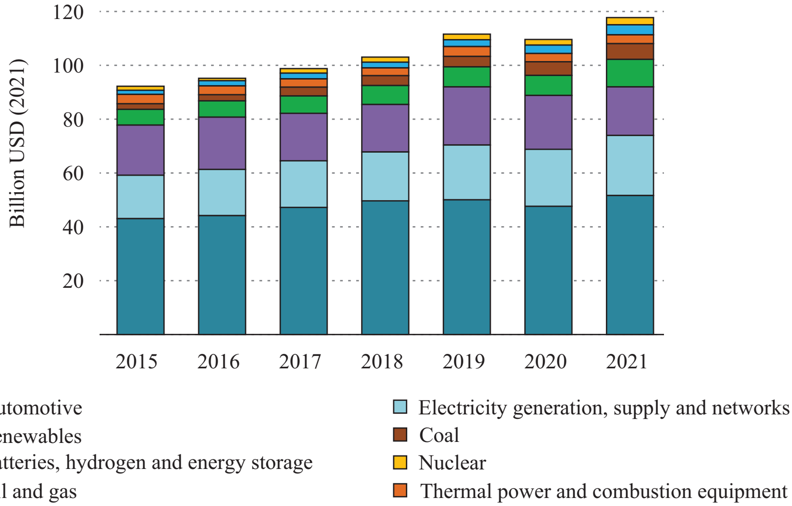


FIGURE 6.7 Energy R&D spending by listed companies by sector, 2015–2021. Firms' R&D spending includes reported R&D expenditure by companies active in sectors dependent on energy technologies, including energy efficiency technologies, where possible. Automotive includes technologies for fuel economy, alternative fuels, and alternative drivetrains. Fuel cells are included with hydrogen. To allocate R&D spending for companies active in multiple sectors, the shares of revenue per sector are used in the absence of other information. Classifications are based on the Bloomberg Industry Classification Standard. All publicly reported R&D spending is included, although companies domiciled in countries that do not require R&D spending to be disclosed are under-represented. Depending on the jurisdiction and company, publicly reported firms' R&D spending can include capitalized and non-capitalized costs, from basic research to product development.

Source: IEA (2022b), World Energy Investment 2022, IEA, Paris https://www.iea.org/reports/world-energy-investment-2022, License CC by 4.0.

Venture capital

Venture capital funding for clean energy technology startups constitutes a significant proportion of total global R&D spending. This funding is crucial for taking many market-ready technologies through the high-risk stages to scale and maturity. The storage infrastructure and storage technologies have grown by the greatest rate in recent years. In 2019, total investment in energy technologies stood at $16.5 billion, with an approximately $4.5 billion investment in hydrogen technologies in their high-risk early stages (see Figure 6.8).

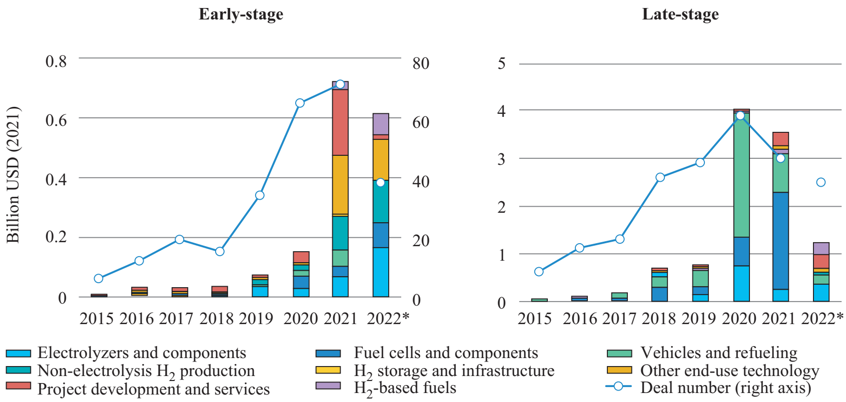


FIGURE 6.8 Venture capital investment in clean energy startups related to hydrogen, 2015–2022. Notes: H_2 = hydrogen. Early-stage deals are defined as seed, Series A, and Series B transactions. Large deals in these categories above a value equal to the 90th percentile growth equity deals in that sector and year are excluded and reclassified as later-stage investments. Later-stage deals also include growth equity, late-stage private equity, buyouts, and public investments in private equity.

Source: IEA (2022c), Global Hydrogen Review 2022, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022, License CC by 4.0.

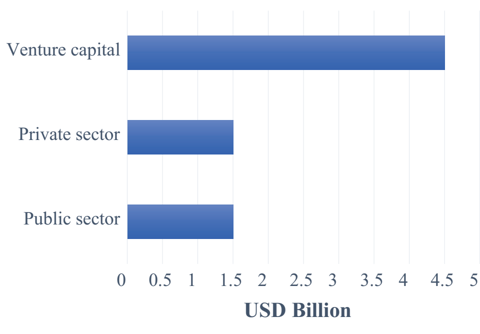


FIGURE 6.9 Global R&D spending on hydrogen technologies.

Source: Authors.

Combining the three primary sources of R&D funding, global spending on hydrogen technologies was $7.5 billion in 2021 (see Figure 6.9). In the same year, the hydrogen generation market was worth $130 billion and the approximate ratio of R&D invested to revenue was 5.7%. Recalling Steven Chu's recommendation of reinvesting 10% of all revenue in R&D, current R&D spending on hydrogen-specific technologies is low; however, signs of growth in hydrogen R&D are evident. As mentioned earlier, since the sales of hydrogen and equipment are expected to be $2.5 trillion by 2050 (Hydrogen Council 2017), the question of whether global R&D can grow at the pace required to support the expanding market remains. In Saudi Arabia, the anticipated level of hydrogen R&D funding must be based on expected revenue goals, the ratio of home-grown to imported technologies, and the cost of broader innovation ecosystem development, which requires comprehensive study.

TRLs of hydrogen technologies

Innovation and technology development, from basic science research to commercially feasible solutions to industrial deployment, is a long and arduous process typically tracked in TRLs. These TRLs are approximately translated into concept (1–3), small (4), large prototype (4–6), scale-up demonstration (7–8), market adaptation (9–10), and maturity (11), as described in Appendix 1 (IEA 2020b). These are followed by steps that incorporate business models and competitiveness, supply chain management, human capacity building, policy readiness, finance, and public acceptance (Safari, Roy, and Assadi 2021). Vulnerabilities may appear at any stage of the development of an innovative technology. Hence, the active role of the public and private sectors and, more recently, venture capitalists has been vital for climate innovations, especially considering the expansion of this process.

The technologies in Figure 6.10 are already in the large prototype stage (TRL4 or above), and their cost functions and commercialization pathways are known. However, taking them to the stages of market adaptation and maturity within the required timeframe is a crucial challenge. Many new technologies not considered today may emerge from the present time to 2050. Hence, basic or fundamental research (TRL1–4) that develops a concept to a small prototype is vital for the fresh infusion of new technologies in the prototype stage. Fundamental academic research that develops a concept to a prototype usually occurs at TRL1–6.

TRL4–6 are common within the academia–industry interface and provide a space for technology transition. At this point, the technology is proven in the laboratory, but sizeable systems have not yet been built. Engineering, material, and scale-up issues may arise, which can threaten further development. As this stage is perceived as high risk, many technologies lack funding and do not survive. Alternatively, if a technology company decides to invest, it insists on full ownership to mitigate the risks and improve its potential profitability. The last section of this chapter addresses the importance of technology transition from universities and research institutions to industry.

Figure 6.11 shows the TRLs of hydrogen and allied technologies. Two salient points are noteworthy. First, advanced technologies related to both green hydrogen

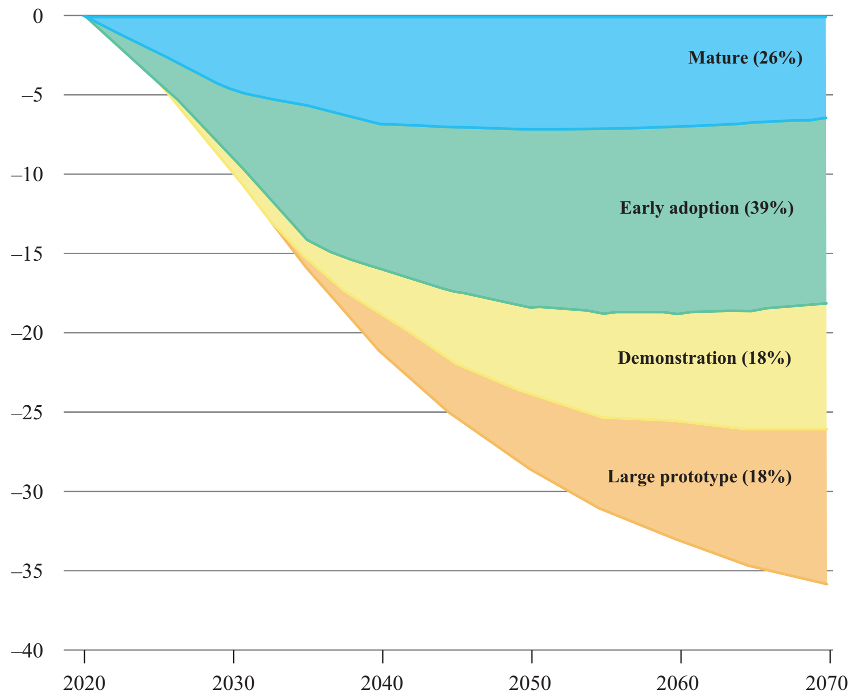


FIGURE 6.10 CO_2 emissions reductions in the global energy sector by technology maturity, 2019–2070.

Source: IEA (2020b). IEA, Global energy sector CO_2 emissions reductions by current technology maturity category in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019–2070,IEA,Parishttps://www.iea.org/data-and-statistics/charts/global-energy-sector-co2-emissions-reductions-by-current-technology-maturity-category-in-the-sustainable-development-scenario-relative-to-the-stated-policies-scenario-2019-2070, IEA License CC by 4.0.

(alkaline, proton exchange membrane) and blue hydrogen (autothermal reformer with CCUS) are ready for market penetration, followed by other technologies such as solid oxide electrolyzer cell and partial oxidation. Second, crucial storage and distribution technologies have already reached maturity.

Figure 6.12 shows the TRLs of hydrogen end-use technologies. This figure shows that hydrogen use in light-duty vehicles and buildings is already mature and that hydrogen storage in salt caverns is fast approaching market readiness. Moreover, many hydrogen applications across industries are at the threshold of large demonstration (e.g., direct iron reduction, high-temperature heating, 100% hydrogen in gas turbines, hydrogen in internal combustion engines, and small aircrafts). If and when the necessary innovation gaps are bridged, these applications will take off, raising market demand for hydrogen. Hence, the time is ripe for elevating these advanced technologies to higher TRLs. Further, many potentially disruptive technologies in the pipeline will need fundamental research at universities.

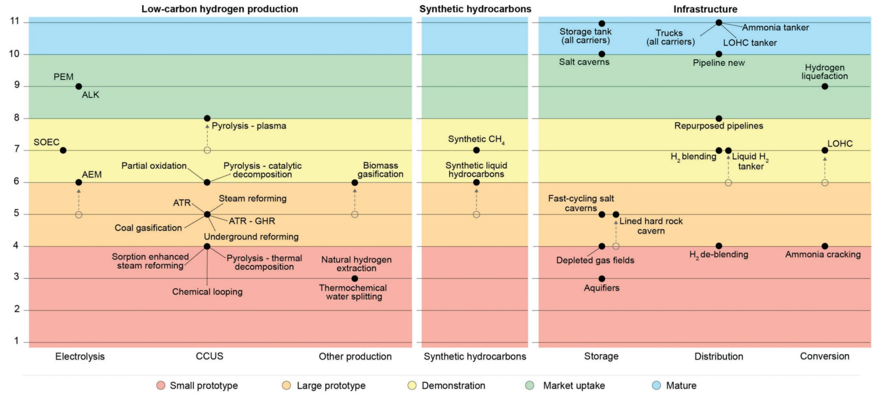


FIGURE 6.11 TRLs of hydrogen production, storage, and distribution technologies[15]. Notes: AEM = anion exchange membrane; ALK = alkaline; ATR = autothermal reformer; CCUS = carbon capture, utilization, and storage; CH_4 = methane; GHR = gas-heated reformer; LOHC = liquid organic hydrogen carrier; NH_3 = ammonia; PEM = proton exchange membrane; SOEC = solid oxide electrolyzer cell; H_2 = hydrogen. Biomass refers to both biomass and waste. The arrows show the changes in TRLs due to progress in the last year. For those technologies in the CCUS category, the TRL refers to the concept of coupling production technologies with CCUS and high CO_2 capture rates. Pipelines refer to onshore transmission pipelines. Storage in depleted gas fields and aquifers refers to pure hydrogen, not blends. LOHC refers to the hydrogenation and dehydrogenation of liquid organic hydrogen carriers. Ammonia cracking refers to low-temperature ammonia cracking. The TRL classification is based on IEA (2020c).

Source: IEA (2022), Global Hydrogen Review 2022, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022, License CC by 4.0.

Fundamental research and patent landscape in hydrogen technologies

Understanding innovation trends through academic research papers and patent analyses constitutes a critical input for national R&D investment strategies. A recent bibliometric study of journal articles on green hydrogen research identified several major research themes and diverse interdisciplinary fields (Raman et al. 2022). Figure 6.13 shows four colored clusters that identify the keywords used in journal articles to shed light on overlapping areas of hydrogen research. The red (the largest cluster) shows hydrogen as renewable energy, including the keywords of hydrogen, green hydrogen, hydrogen storage, fossil fuels, fuel cells, carbon dioxide, solar power generation, and renewable energies. The green cluster comprises hydrogen production themes, including the keywords of hydrogen production, electrocatalysts, water splitting, oxygen, oxygen evolution reaction, electrolytes,

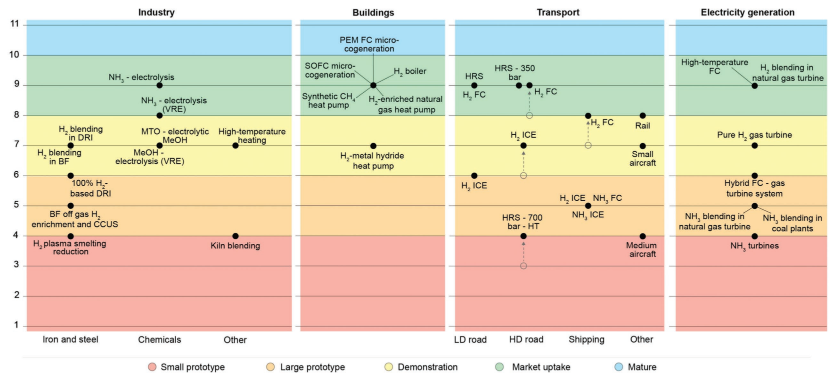


FIGURE 6.12 TRLs of hydrogen end-use technologies[15]. Notes: BF = blast furnace; DRI = direct iron reduction; FC = fuel cell; HRS = hydrogen refueling station; HD = heavy-duty; HT = high throughput; ICE = internal combustion engine; LD = light-duty; MeOH = methanol; MTO = methanol to olefins; NH_3 = ammonia; PEM FC = proton exchange membrane fuel cell; SOFC = solid oxide fuel cell; VRE = variable renewable electricity; H_2 = hydrogen. The ‘other’ industry includes all industrial sectors except methanol, ammonia, and iron and steel production. The ‘other’ transport includes rail and aviation. The arrows show the changes in TRL due to progress in the last year. Cogeneration refers to the combined production of heat and power. The TRL classification is based on IEA (2020).

Source: IEA (2022c), Global Hydrogen Review 2022, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022, License CC by 4.0.

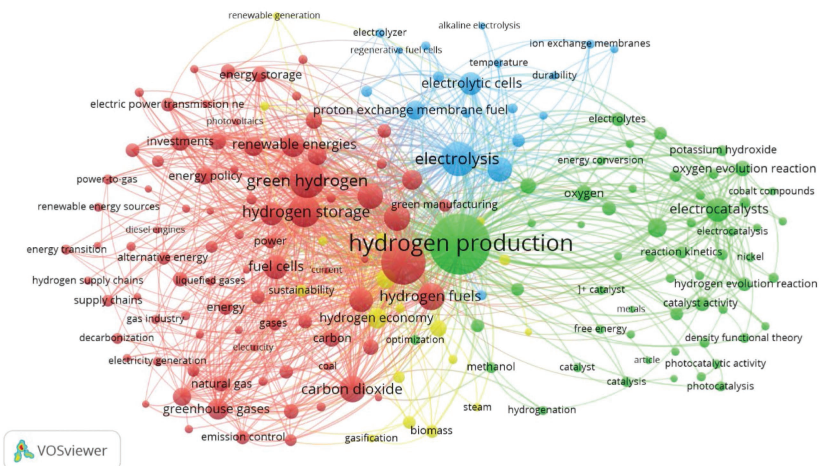


FIGURE 6.13 Keyword co-occurrence network analysis showing the four significant themes in hydrogen research journal articles as clusters.

Source: Raman et al. (2022)[22].

and catalysts. The blue cluster represents the hydrogen production process, including the keywords of water electrolysis, electrolytic cells, electrolysis, electrolyzers, polyelectrolytes, solid oxide fuel cells, alkaline water electrolysis, and proton exchange membrane fuel cells. Finally, the brown cluster includes the keywords of hydrogen economy, biomass, sustainability, steam reforming, hydrogen fuels, and gasification. These research themes highlight the topics on which university research can focus on to develop hydrogen technologies and support innovation.

International collaboration in hydrogen research is essential. The network analysis in Figure 6.14 provides insights into which countries are leading the way in fundamental research on hydrogen. The figure groups the countries conducting collaborative research on green hydrogen into four clusters based on published scholarly articles (Raman et al. 2022). China and the United States (green cluster) publish the most journal papers (10% each), followed by Germany (red). The yellow cluster is led by Italy, with the United Kingdom and other EU countries as part of this group. Saudi Arabia (blue) has high scholarly output in collaboration with countries such as Malaysia, Egypt, Denmark, and the UAE. The high collaboration evident in the network analysis indicates joint global efforts to enhance science by backing the hydrogen economy.

R&D investment from public and firm funding leads to innovation, of which patents are a significant marker. Recent studies on the patents of hydrogen-related technologies include the topics of production, storage, distribution, and utilization

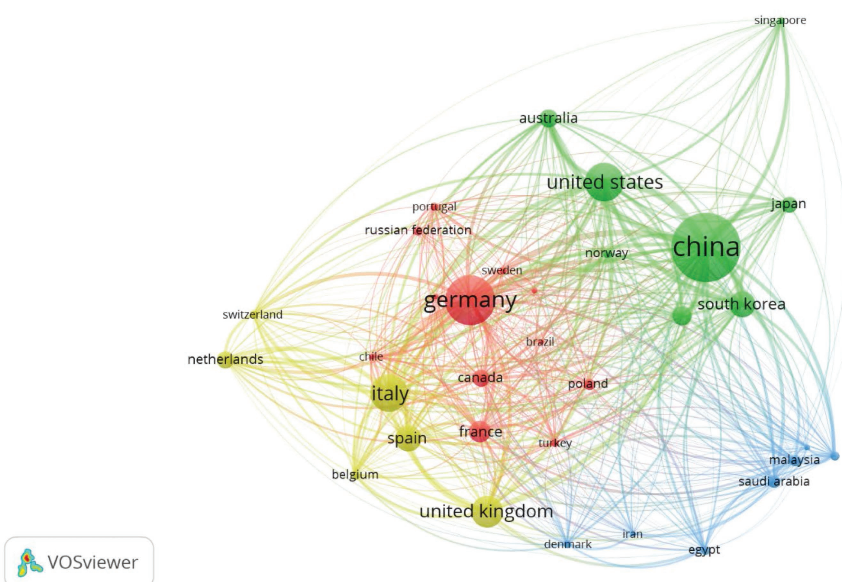


FIGURE 6.14 Bibliographic network of the leading countries contributing to hydrogen research.

Source: Raman et al. (2022)[22].

covering 2010–2020 (Cammeraat, Dechezleprêtre, and Lalanne 2022; Choi and Woo 2022; IP Australia 2021).

The authors of these studies aimed to identify the relationships among sectors and unexplored technological opportunities to build knowledge for investment and institutional support. The regional division of R&D spending and patent analysis on hydrogen technologies suggests that countries such as China, the United States, Japan, South Korea, Germany, France, Taiwan, the United Kingdom, and several other EU countries have invested the most until now (see Figure 6.15). Comparing public R&D spending (Figure 6.5) with patent ownership (Figure 6.15), most countries appear in both figures, indicating that countries investing public money in R&D are maximizing their innovation outputs in terms of patents.

The divisions of patent families in specific technologies for production, storage and distribution, and utilization are shown in Figures 6.16–6.18, respectively. Within the ambit of hydrogen production, electrolysis (green hydrogen) and fossil

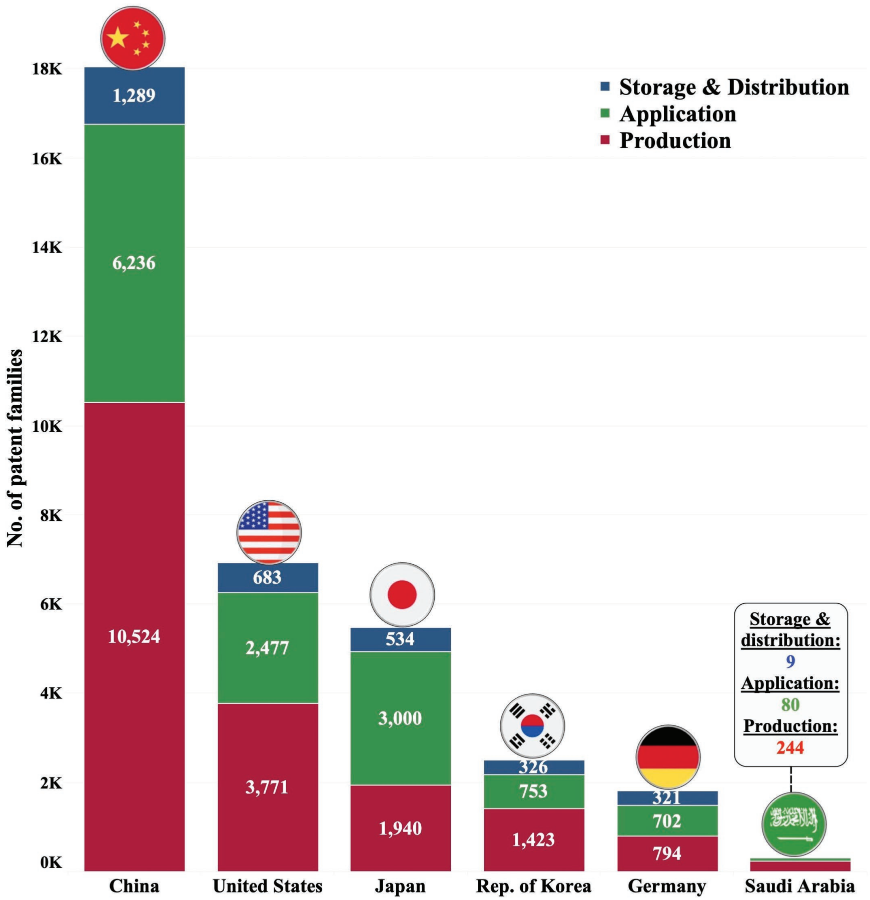


FIGURE 6.15 Leading countries' patent families in hydrogen-related technologies.

Source: IP Australia (2021)[25].

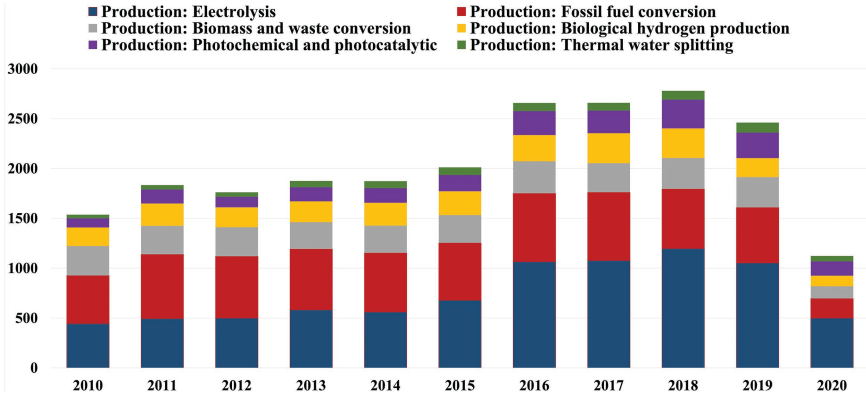


FIGURE 6.16 Patents in hydrogen production technologies, 2010–2020.

Source: IP Australia (2021)[25].

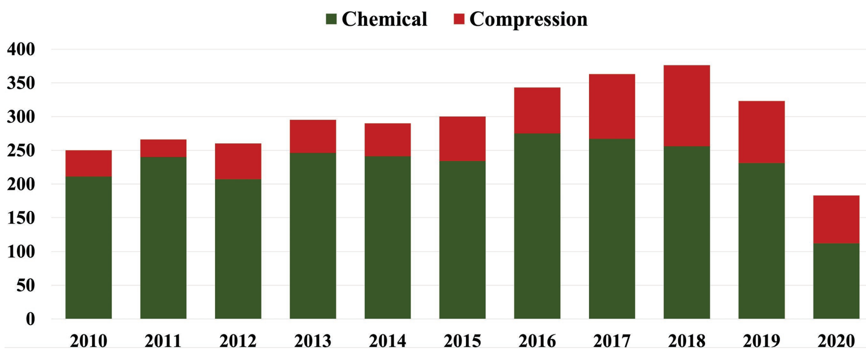


FIGURE 6.17 Patents in hydrogen storage and distribution technologies, 2010–2020.

Source: IP Australia (2021)[25].

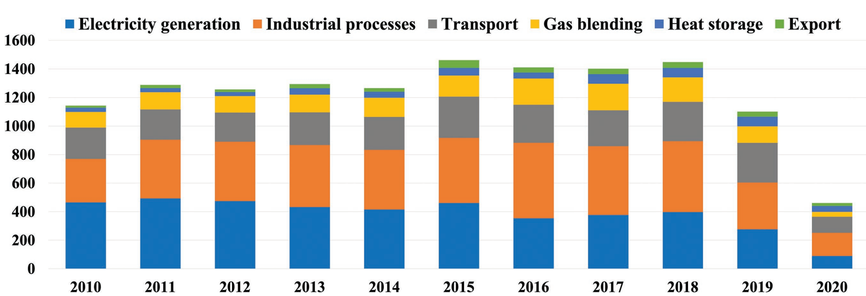


FIGURE 6.18 Patents in hydrogen utilization technologies, 2010–2020.

Source: IP Australia (2021)[25].

fuel conversion (blue hydrogen) are leading the patenting trends. However, research on technologies at low TRLs, such as photochemical, photocatalytic, and thermal water splitting, is making steady progress. In the storage and distribution domain, chemical methods are gaining more research focus than their mechanical counterparts. Chemical procedures for storing hydrogen include liquid organic hydrogen carriers (LOHCs), metal hydrides, ammonia, and methanol. By contrast, mechanical methods involve compression and cryogenic cooling. Finally, concerning hydrogen utilization, sectors such as the power, processing, and transport industries take the lion's share of patents. Technologies for gas blending, heat storage, and export are also becoming significant. The temporal patterns show that patenting activities slowed down in 2019–2020 due to the COVID-19 pandemic after peaking in 2018.

Saudi Arabia has made steady progress in this regard, with 324 patent families (filed, accepted, and granted) for hydrogen technologies by mid-2021: 244 for production, 80 for applications, and 9 for storage technologies (Choi and Woo 2022). A different set of intellectual property (IP) databases distills down to the specific patents granted to Saudi Arabian firms in hydrogen-related technologies (Choi and Woo 2022)[23]. Table 6.1 presents the subject matter of several of these granted patents.

Saudi Arabian companies such as Saudi Aramco and Saudi Basic Industries Corporation (SABIC) have consistently conducted R&D on hydrogen and allied technologies such as CCUS. Over the decades, many universities have also performed fundamental research that directly benefits hydrogen technologies. However, focused innovation and systematic R&D investments of the required scale and magnitude are lacking.

Hydrogen technologies relevant for Saudi Arabia

The authors solicited the views of the government, academia, and industry experts to list the technologies most suitable for Saudi Arabia. Most of these topics are covered in subsequent chapters of this book that focus on technology (Chapters 15–27). These chapters together list all the promising technologies and plausible roadmaps in the hydrogen domain best suited to meeting Saudi Arabia's climate goals; industrial objectives; and long-term environmental, social, and governance priorities. We also map the scientific fields associated with the identified technologies and current research and patenting trends in hydrogen, as shown in Table 6.2.

A roadmap for R&D and innovation in hydrogen technologies

A hydrogen technology roadmap will invariably be a subset of the broader innovation ecosystem planning for the Kingdom. This ecosystem must not only develop home-grown technologies but also absorb and improve technologies from

TABLE 6.1 Patents owned by Saudi Arabian firms in hydrogen-related technologies, 2010–2020

Firm name	*No. of patents granted*	*Broad subject matter*
Saudi Arabian Oil Company (Aramco)	63	Autothermal reforming, thermo-neutral reforming, hydrocarbon processing, gasification, electrolysis-solid oxide fuel cells
Saudi Basic Industries Corporation (SABIC)	27	Direct iron reduction, Fischer–Tropsch (F.T.) synthesis, hydrogen catalysts, steam methane reforming, photocatalysis, thermochemical water splitting, photoelectrochemical water splitting
King Fahd University of Petroleum and Minerals (KFUPM)	23	Steam methane reforming, desalination
King Abdullah University of Science and Technology (KAUST)	13	Metal-organic framework, direct air capture, membranes, reforming, dry reforming, ammonia cracking, nanotechnology, catalysts
King Saud University (KSU)	2	Photocatalytic water splitting
King Abdulaziz University (KAU)	2	Partial oxidation
Petrobras S.A.	2	Catalysis
King Abdulaziz City for Science and Technology (KACST)	1	Electrocatalysis
Imam Abdulrahman bin Faisal University (IABFU)	1	Photocatalysis

Source: Choi and Woo (2022).

external sources, as stated in studies on innovation in Arab countries (Bizri 2013, 2018). These studies have found two ways of doing this: (1) adapting innovations from external sources to local priorities and recipient ecologies and (2) developing home-grown innovations when external innovations are inadequate and adaptive, and original R&D efforts are required.

The need for innovation to be embedded early and widely within processes aimed at socioeconomic development, education, and vocational training has also been underlined (Bizri 2013, 2018). Considering the aforementioned and recognizing that not all technologies need domestic development, we classify the technologies into four categories: (1) basic research, (2) firm research and technology translation, (3) technology acquisition, and (4) technology licensing or transfer. These categories, as presented in Table 6.3, relate to technology maturity, institutional

TABLE 6.2 Mapping the scientific fields to technologies in the context of hydrogen research

Scientific field	*Hydrogen or enabling technology*
Combustion science	Reforming, gasification, gas turbine, engines, E-fuels, blending
Catalysis	Reforming, chemical processes, hydrogen carriers, ammonia cracking, long-term energy storage
Electrochemistry	Fuel cells, batteries
Membranes and porous media	Desalination, air separation, gas purification, carbon capture
Geology and geophysics	Oil and gas extraction, CO_2 and hydrogen storage, carbon capture
Fluid mechanics and cryogenics	Gas compression, liquefaction, carbon capture
Material and polymer science	Fuel cells, batteries, pipeline transport, reactor materials, recycling, plastics to hydrogen
Chemistry (organic, inorganic)	Ore reduction, heavy industries, refineries, biomass
Biosciences	Biomass to hydrogen, biocatalysts/enzymes
Power electronics	Power grid
Nuclear science	Reactors, power cycles
Engineering	Chemical processes, manufacturing, controls, connectivity, power electronics, grid, sensors integration, digitization, civil engineering (for infrastructure and building work)
Modeling and simulations	Mathematics, statistics, artificial intelligence, computational sciences
Sustainability	Life cycle assessments, technoeconomic modeling, environmental/social/governance, climate and atmospheric sciences

Source: Authors.

type, national strategic thrust, public/private funding, and international collaboration and technology transfers.

Table 6.3 presents a roadmap for hydrogen technology development in the Kingdom, with the selected research areas or technologies chosen from the studies included in this book. The list of technologies is representative if not exhaustive. We consider two time horizons, namely, from now until 2030 and from 2030 to 2050, referred to as the short-term and long-term horizons, respectively. Public spending on R&D increases as we move from right to left, whereas technology maturity increases from left to right. In other words, areas of basic research today (orange) will gradually move from yellow to blue and finally to the green block and become the mature technologies of tomorrow. The green block consists of fully commercial technologies that will lead to infrastructural growth at an industrial scale.

TABLE 6.3 Hydrogen RDDI action plan and roadmap

Technology maturity (2022)	*Concept development TRL ≤ 4*	*Small and large prototypes: startups: 4 ≤ TRL ≤ 6*	*Startups, large demonstration; novel technologies: 6 ≤ TRL ≤ 9*	*Deployment; mature technologies: 8 ≤ TRL ≤ 11*
Activity	Basic research	Technology development, translation, and firm research	Technology acquisition and collaboration	Technology transfer and licensing
RDDI action	Build strategic institutions and develop human capital; increase international research collaborations in hydrogen-specific and overlapping fields	Enhance academic to industry research translation; conduct objective-based research in industrial labs	Acquire technology companies owning niche technologies by domestic entities and joint ventures	Perform technology licensing from global companies to domestic entities; technologies are mature and do not require domestic development
Desired outcome	Fundamental research in scientific and engineering disciplines; scouting potential innovative solutions/concepts and technologies; preparing an educated and skilled workforce	Pre-pilot scale demonstration; component performance assessment; seeking industrial partners for technology deployment	Pilot-scale demonstration with industrial partners supported by venture capital; risk retirements; system performance assessment	Business contracts and offtake agreements, plant setup, and commissioning; supply chains; economies of scale
Funding source	Public funds; university endowments	Public/private collaboration	National companies/ venture capital investments, sovereign wealth funds (Taqnia); corporate venturing (e.g., Aramco, NEOM, Abdul Lateef Jamil)	Private/national company partnerships
Time for commercial adaptation	5–20 years	3–5 years	2–3 years	<2 years
Examples	Hydrogen/NH_3 combustion; steam calcination; PV; sour gas cracking	Ammonia cracking; DAC (Aramco–KAUST collaboration)	Acquiring companies in the league of Monolith and Proton Energy	Jizan IGCC and NEOM

TABLE 6.3 (Continued)

Technology maturity (2022)	*Concept development TRL ≤ 4*	*Small and large prototypes: startups: 4 ≤ TRL ≤ 6*	*Startups, large demonstration; novel technologies: 6 ≤ TRL ≤ 9*	*Deployment; mature technologies: 8 ≤ TRL ≤ 11*
Short-term critical (<10 years): criticality increases from left to right	Membranes; catalysts electrochemistry, materials water splitting, photo-electrochemical water splitting, plasma advanced nuclear reactors/cycles; hydrogen from sour gas; hydrogen/NH_3 combustion; hydrogen steam calcination	NG pyrolysis; DAC; CCC; hydrogen storage in salt caverns; synthetic fuels; hydrogen/NH_3 for ICEs; waste to hydrogen	Advanced PV and batteries; PEM; ATR and partial oxidation+CCS; nuclear hydrogen; hydrogen pipelines; hydrogen in gas turbines; hydrogen in DRI; power-to-X technologies; waste-to-hydrogen; NH_3/methanol marine fuels; F.T. synthesis fuels (eKerosene); AI, connectivity; digitalization	Steam methane reforming+CCS retrofit; amine-based CCS; geological storage of CO_2; GW-scale AWE; petroleum residue gasification+CCS; FCEVs; fuel-switching liquid to NG/hydrogen in power generation
Long-term critical (>10 years); criticality decreases from left to right	Basic research on novel technologies unknown today	Mining for critical minerals	Alternative materials	TW scale solar/wind-driven electrolysis
		Renewable desalination	Flexible and hybrid renewables	Mature hydrogen/CO_2 storage and utilization
		Hardware manufacturing	AEM, solid oxide fuel cells	Grid stabilization
		Heavy industry applications	GW-scale nuclear H_2	
		Hydrogen and synthetic fuels for aviation	CSP-driven electrolysis	
		Hydrogen fuel cells for shipping	Large-scale DAC	
			Direct NH_3 gas turbines/fuel cells	

Source: Authors.

Notes: AWE = alkaline water electrolysis; PEM = polymer exchange membrane electrolysis; AEM = anion exchange membrane; SOEC = solid oxide electrolyzer cell; NG = natural gas; ATR = autothermal reforming; DAC = direct air capture; CCC = cryogenic carbon capture; FCEV = fuel-cell electric vehicle; ICE = internal combustion engine; DRI = direct reduced iron steel; PV = solar photovoltaic; CSP = concentrated solar power; AI = artificial intelligence, GW = gigawatt; TW = terawatt; H_2 = hydrogen; NH_3 = ammonia. Examples of national companies: Aramco, SABIC, Ma'aden, and Saline Water Conversion Corporation. Private sector companies include Air Products, Baker Hughes, ThyssenKrupp, and ACWA Power.

Need for an RDDI ecosystem and technology translation in Saudi Arabia

This section provides an overview of the RDDI ecosystem in Saudi Arabia and recommends actions to propagate hydrogen research.

RDDI ecosystem in Saudi Arabia

Four important matrices for understanding RDDI in a country are gross expenditure on R&D (GERD) as a percentage of Gross Domestic Product (GDP), research personnel per million population, the Global Innovation Index (GII), and the World Competitiveness Ranking. We examine how Saudi Arabia is performing on these four measures.

GERD as a percentage of GDP and researchers per million population

Figure 6.19 shows GERD as a percentage of GDP and research personnel per million population for selected countries. Total global R&D expenditure reached $2.3 trillion (purchasing power parity basis) in 2021, overcoming COVID-19-related disruptions (Heney 2021). The United States ($598 billion) and China ($621 billion) were the largest spenders, accounting for 2.88% and 1.98% of their respective GDPs. The data suggest that Africa, South America, and the Middle East's combined R&D was 5% of the global R&D spending, even though these regions

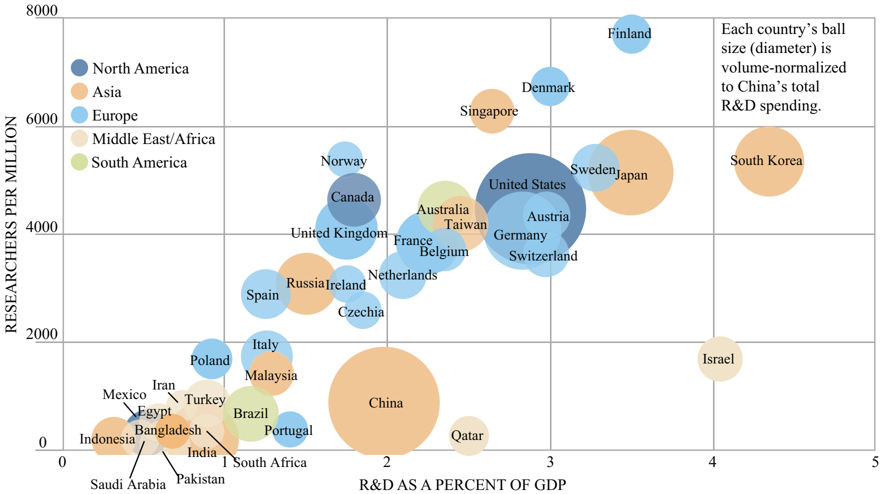


FIGURE 6.19 A global snapshot of GERD as a percentage of GDP and researchers per million population.

Source: Heney (2021) with permission.

account for more than 13% of the world's GDP. This regional disparity in R&D spending is a clear red flag for countries that want to break out of this laggard group and be tomorrow's technology leaders. Saudi Arabia spent $8.9 billion on R&D in 2019, about 0.5% of the GDP, ranking 32nd globally (Heney 2021). Further, Saudi Arabia had a low number of researchers (453) per million population, indicating that the institutional infrastructure and human resources for S&T require a more significant expansion to support the needed R&D growth.

GII and world competitiveness ranking

The GII, published by the World Intellectual Property Organization, provides an annual assessment of the innovation capabilities of countries in the form of innovation inputs and outputs. In the GII, Saudi Arabia is categorized as a high-income country and is ranked 41st of the 48 countries in this group. Saudi Arabia's innovation outputs are low compared to its inputs, leading to a low rank among the high-income group countries. Figure 6.20 shows the relationship between the

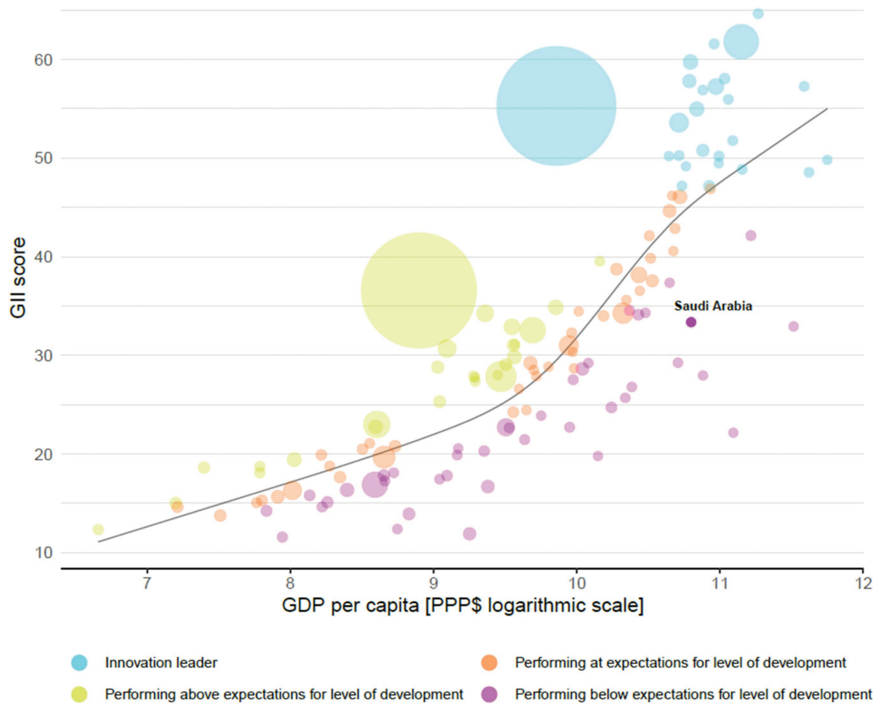


FIGURE 6.20 The positive relationship between innovation and development. PPP: Purchasing power parity.

Source: WIPO (2022). Global Innovation Index 2022: What is the future of innovation-driven growth? Geneva: WIPO. DOI 10.34667/tind.46596. Attribution 4.0 International (CC by 4.0).

development stages and innovation levels of countries, depicted as the GII and GDP per capita. Saudi Arabia is performing below its developmental status, implying that innovation investments do not produce the desired impact. Recently, consistent efforts have been made to improve the country's innovation ranking. Saudi Arabia has jumped 15 places from 65th in 2021 to 51st in 2022. Figure 6.21 shows its performance on the seven GII pillars. In the market sophistication category, the Kingdom performs on par with its high-income peers; however, in the institutions, human capital and research, knowledge and technology outputs, and infrastructure categories, its performance remains low. The GII and indicators provide helpful insights into areas for improvement in the innovation ecosystem in Saudi Arabia.

The World Competitiveness Ranking published by the Global Competitiveness Center for the International Institute for Management Development assesses countries based on how their institutions, policies, and other relevant factors provide prosperity to their citizens. The World Competitiveness Ranking includes institutions, infrastructure, primary and higher education, and the ability to harness technology and innovation as some of the 12 essential pillars for building an innovation ecosystem. Saudi Arabia was placed 24th in 2022 after registering an eight-position jump over its 2021 rank of 32 (International Institute for Management Development 2022). This large jump underscores the country's investment and progress in education, research, and innovation. Progress in infrastructure over

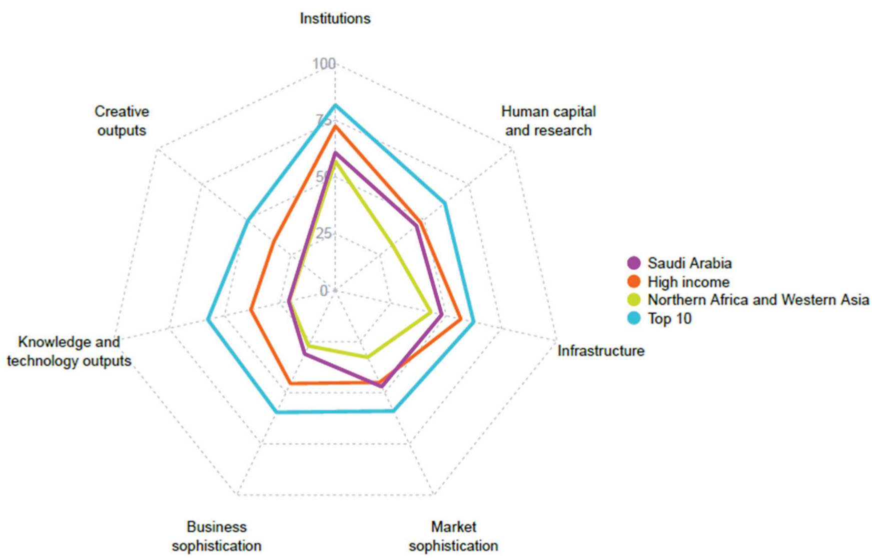


FIGURE 6.21 The seven GII pillar scores of Saudi Arabia are benchmarked against those of other high-income group economies in North Africa and Western Asia.

Source: WIPO (2022). Global Innovation Index 2022: What is the future of innovation-driven growth? Geneva: WIPO. DOI 10.34667/tind.46596. Attribution 4.0 International (CC by 4.0).

the previous years was particularly noticeable, with the following sub-rankings in the infrastructure category: basic infrastructure (20), technological infrastructure (30), scientific infrastructure (30), and education (37). The challenges Saudi Arabia faces with regard to improving its competitiveness are the need to accelerate economic diversification, promote renewable energy, reduce carbon emissions, and close the gap between higher education and job markets.

Institutional framework in Saudi Arabia

The Kingdom's research infrastructure is built around its major universities and associated research centers, strategic research institutions (e.g., King Abdulaziz City for Science and Technology (KACST), KA CARE), and national companies (Aramco, SABIC). The Hydrogen Innovation and Development Center at NEOM recently entered this list (Saudi Press Agency 2022). Table 6.4 lists some of the top globally ranked universities in the Kingdom. KAUST's endowment is one of the largest in the world, a factor that is core to its success. Major financial support for Saudi universities also comes from the government's fiscal budget. This is different from the endowment model on which some universities rely.

TABLE 6.4 Major universities in Saudi Arabia

University	*US News ranking*[29]	*Endowment (USD billion)*
King Abdulaziz University, Jeddah	44	1
King Abdullah University of Science and Technology (KAUST), Thuwal	97	20
King Saud University, Riyadh	266	2.7
King Fahd University of Petroleum and Minerals (KFUPM), Dhahran	445	n/a

Source: US News ranking from US News & World Report (2022). Endowment amount from Wikipedia.

These universities have top-100 ranked departments and high research output in disciplines crucial for global energy transition research and innovation, including chemistry, chemical, electrical, electronics, computer science, mechanical engineering, biotechnology, energy and fuels, and material and polymer sciences. KAUST is a remarkable success story that shows what is possible with political will, immaculate planning, committed funding and resources, and a vast pool of local and international human talent. Within 10 years of its inception, it broke into the top-100 best global universities (US News & World Report 2022). KAUST is first in the Middle East and sixth in the world according to the latest Nature Index, which ranks the research output of 175 young universities (aged 50 years and under; Conroy 2019). As exemplified by KAUST, institutional growth can be a future template for universities and research institutions that need to support R&D and innovation goals.

Research, development, and innovation authority

Saudi Arabia's focus on RDDI is becoming a central theme for diversifying its economy, achieving its long-term socioeconomic goals, and building a knowledge-based economy. The Kingdom recently established its research, development, and innovation authority (RDIA), targeting a GERD of 2.5% of GDP by 2040 and intending to create human resources to support this objective. The goals are to enable Saudi Arabia to become an R&D and innovation powerhouse, develop into the region's largest economy, and develop Saudi universities and research institutions such that they are on par with the best in the world. Collaborating and co-funding with research institutions, global companies, non-profit organizations, private companies, and startups are prioritized. The strategy sets ambitious goals, including raising the country's World Competitiveness Ranking from 24 (2022) into the top 10 and having 5 of its universities in the top 200 internationally. Increasing public/private partnerships, building an extensive talent pool, and creating high-value jobs in S&T are part of the R&D and innovation strategy. The four priorities for R&D and innovation for the next two decades are as follows:

1 Health and wellness: Infrastructure for medical research, biotech, and digital healthcare
2 Environmental sustainability and meeting essential needs: CCUS technologies and sustainable technologies for low-cost electricity generation
3 Energy and industry: Alternative energy sources such as green hydrogen, solar, and wind and focusing on the mining sector
4 Future economies: NEOM and the Red Sea Project, digital technologies, deep sea, and space exploration

The strategies to achieve these R&D and innovation targets and investing the allocated funds are two essential components that warrant careful consideration. Both will require an assessment of not only the R&D ecosystem in the Kingdom but also the time it takes to develop the culture, interest, and human resources. A sustainable innovative culture depends on local talent having a desirable mindset and driving the development of indigenous technology or adapting and improving existing technology to local conditions. This signifies a move from a mostly consumer-led society and economy to a productive society and economy built on manufacturing and production.

While the development of human resources has been ongoing for a long time, more work is needed to improve its integration and impact. This can be achieved by creating a conducive environment such as that at KAUST in which R&D and translation are the focus. One approach could be to use existing universities and national laboratories as the research focus. Another is to build technology acceleration hubs that create the desired innovation environment for entrepreneurship to flourish.

Another effective approach would be to establish strategic links with leading research hubs globally to exchange personnel and expertise as well as develop IP collaboratively. These well-established and reputable institutions would benefit from offering their expertise to a country that needs them, while local talent could be exposed to state-of-the-art research practices. Although such a win/win model has been demonstrated numerous times, it can only succeed if the connection occurs at the researcher level once an agreement has been reached. The additional benefits are the identification, adaptation, and further development of the external technology needed by the Kingdom, particularly to grow the SME sector, which is lagging behind those in other economies of the same size.

The global nature of the decarbonization challenge, including the hydrogen energy vector, and the imposed short timescale require cooperation between countries and organizations worldwide. Developing and adequately funding multinational consortia that address the key challenges related to hydrogen and decarbonization could be highly beneficial. Such an approach could be developed at the regional or industry level. For example, most Gulf Cooperation Council countries plan to develop a blue hydrogen infrastructure and adapt existing technologies to produce it. Cooperation between the research institutions in Gulf Cooperation Council nations could accelerate the development of this infrastructure by offering solutions to intractable regional problems. The joint funding of these efforts would also help reduce the burden and maximize the benefits.

Considering the relatively low base of low-carbon technology development and manufacturing in Saudi Arabia, it is advisable to focus on the demonstration activities of promising energy technologies to help de-risk adaptation, train the local workforce, and enhance technology transfer. The Kingdom is experiencing an economic boom, and decarbonization is high on the agenda. Investing in demonstration projects would give it an advantage in large-scale deployment over its competitors. This short-term strategy could also help generate new research streams and accelerate the development of new IP that can be exploited both locally and internationally.

Translating university research into economic goals: KAUST's knowledge exchange model

This section describes the challenges with regard to developing the hydrogen economy in Saudi Arabia, including the importance of translating university research into outputs that benefit the economy. Politicians, policymakers, and research funders globally are seeking to translate university research into public benefits; however, no clear model that can be described as sustainable, reproducible, or even measurable has evolved. This is despite several decades of intense debate. This section discusses the challenges inherent in the transfer of university research, the barriers that exist, and the misconceptions associated with the activity. Finally, it outlines approaches that seem to be effective.

The KEM framework described in the following sections is technology-agnostic and can be applied to advancements in most areas of science and engineering. The translation of university research into an economic base is also known as technology transfer, commercialization, and knowledge exchange. It describes the process by which university research, usually 'fundamental,' but sometimes 'applied,' finds its way into the economy. Over time, many attempts have been made to capture, quantify, and refine this process. Figure 6.22, created by one of the authors (Cullen) in the early 2000s, has often been used to contextualize the problem to be solved (Campbell et al. 2020; Holi, Wickramasinghe, and van Leeuwen 2008; Finne et al. 2009).

Given that we seek to describe a system that has challenged some of the best policymakers globally, it appears deceptively simple. First, universities conduct research, the primary outputs of which are new knowledge as well as new and better researchers. These are thus the key outputs for university research: knowledge and talent. Such primary outputs manifest in many ways, including publications, processes, innovation, skills, technology, IP, and know-how. KAUST conducts approximately $500 million of research per annum and, therefore, is creating these outcomes at a large rate. Multiplied across the university sector worldwide, these

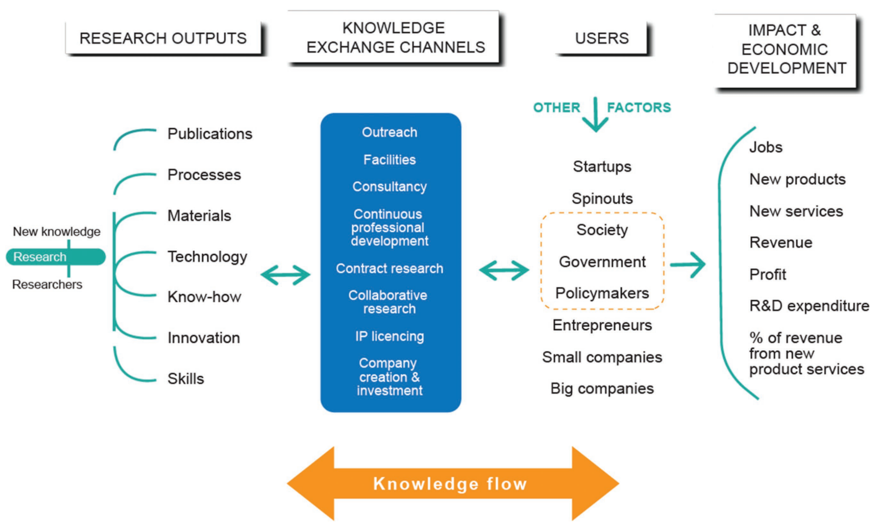


FIGURE 6.22 Knowledge exchange model.

Source: Authors.

outputs are produced on a staggering scale, but how do they translate into an economy and create public benefits? There are two distinct pathways:

- Human capital: The skills, knowledge, and know-how of students are disseminated into the workforce, and each student contributes to the economy during their career. Although this is thought to be huge, it is immeasurable, much like throwing a handful of stones into the sea and measuring the additional energy of the waves.
- Technological capital: Codified knowledge, IP, and faculty know-how form a relatively well-defined knowledge set. From this, we seek to create knowledge exchange channels (Figure 6.23).

Knowledge exchange channels represent the mechanisms through which universities transfer tacit knowledge to people who can use it (see Figure 6.23). These startups, spinouts, large companies, SMEs, licensees, and research collaborators take this tacit knowledge, in whatever form, and put it to use in some way. The importance of research users in this model is critical. Research users, who are subject to various other factors, take universities' knowledge and put it to use. These other factors (e.g., Icelandic ash clouds, exchange rate mechanisms, pandemics, Brexit, Ukraine) are important, as they are often much more critical to the user than is technology. These factors play a more intrusive role in the operations of these companies and agencies than university research. Therefore, universities must understand their place and role.

Done successfully, the translation of university knowledge into the SME, large company, startup, and spinout can help them develop a more competitive business model. In doing so, they will create jobs, products, services, GDP growth,

Knowledge exchange channels

Knowledge exchange mechanism (HEIF metrics)	% Revenue
Regeneration and development programs	5
Facilities and equipment services	4
Consultancy	11
Continuous professional development and continuing education	20
Contract research	34
Collaborative research	23
Intellectual property (including sale of shares)	2

FIGURE 6.23 Knowledge exchange channels and revenues. HEIF: Higher Education Innovation Funding; HEFCE: Higher Education Funding Council for England.

Source: Adapted from Coates-Ulrichsen (2014).

happiness, healthiness, wealth, greenness, and many other things that we now refer to generically as 'impact.' If they can demonstrate such impact, in the terms described above, they have achieved their mandate. Unfortunately, this is not yet possible, and the next section explains why.

Implications of the knowledge exchange model

The KEM (Figure 6.22) is a good representation of the system; however, some of its implications can challenge current thinking. The first concerns whether universities create impact. Universities do not create impact (e.g., jobs, products, services) but they help others (e.g., students, startups, licensees) do so. Universities have long told research funders that they create impact. This is a noble endeavor and one that fits with the ethos of the university as an enabler and supporter of impact. If universities can enable their partners (research users, startups, spinouts, entrepreneurs, government partners) to create impact (and they acknowledge universities' input), then everyone wins. This includes companies, the government, and universities commercially, economically, and reputationally, respectively. This is the alignment of different but complementary interests, which will unlock the system.

Another implication of the model is that despite looking linear, it is, in fact 'chaotic' in the scientific sense. It is a cause-and-effect system, the outcomes of which are so unpredictable that they are effectively random. This is the best description of the tech transfer world. Universities perform great research from which new ideas and inventions emerge; however, research is not conducted to create inventions. It is conducted to push forward the boundaries of human knowledge. Inventions tend to be beneficial by-products of this process. This is not the case in industries where research is conducted toward a predetermined goal or objective; by contrast, university research is conducted to better understand the universe. If a valuable invention emerges from this, that is a good thing, but it is not the purpose of university research and neither should it be.

The job of technology transfer personnel is to take these inventions and maximize their benefits to the economy, society, and community. However, given that the starting materials are observations and inventions that flow from research rather than being the objective of research, it is difficult to create a sustainable business model based on IP being delivered from university research. In other words, predicting the impact may be impossible during the university research stage, as too many unknowns, variables, actors, and other factors (as previously described) are involved in making that prediction, leading to chaos. What universities can do is connect researchers with people interested in the research and those thinking about how they might be able to use the outcomes of that research.

This is the conundrum. Academics are assessed and rewarded based on their research and publications. They are not, in general, and despite protestations by some, rewarded for the impact of their research in the economy, community, and society. Hence, why would an academic seek to ‘commercialize their research’ despite the fact that this seems to be what politicians, policymakers, and research funders really want to know?

Recommendations for technology transfer in developing new technologies

Improving the system of translating university research into the desired impact demands taking certain actions and avoiding others.

Do understand and align academic interests with policy interests. Here, policies could be both local and international policies that might impact Saudi Arabia, especially those related to trade (e.g., emissions, carbon, border adjustments). While this sounds relatively straightforward, it has previously resulted in counterproductive approaches, including (1) asking faculty to become entrepreneurs and start companies and (2) rewarding researchers for filing invention disclosures.

In both cases, these factors lead to many ineffective activities that do not answer the fundamental question. Asking faculty to create technology startups is particularly problematic, as it misses the point on so many different levels.

The vast majority of faculty members do not wish to commercialize their IP. They must teach students, research, write proposals, publish papers, and attend conferences. They are extremely busy people. Therefore, asking them to add this strange new commercialization agenda to their work is a challenging task, especially given the uncertainty regarding how likely it is to succeed and how long it will take.

By contrast, all faculty members want their research to make a difference in the world. This points to a simple policy direction. We should aim to encourage and enable connections between researchers and the people who will put their research to use. We should also help researchers engage with people genuinely interested in the research and who can help shape it to maximize its impact. However, while this works for industry-informed research, it is less effective for industry-directed research, as discussed next.

Do not seek to direct university research toward predetermined objectives. As previously stated, the system is chaotic and outcomes cannot be predicted. While some areas are suitable for directed research, this should not be the case with university research, which is characterized by curiosity-driven, investigator-led research.

At the policy level, there is always a temptation to direct resources to those areas with the greatest potential return. However, these are areas viewed through today’s lens, and disruptive technologies being developed in labs are not considered. While broad areas such as food, water, energy, and the environment are sufficient as the focus of research efforts, a more granular focus risks running into the Kodak problem of perfecting technologies that are about to become obsolete.

Do understand where the value lies between university research and industry. A feature of the university/industry interface is that it has become more difficult over time. Universities and companies seem to view each other as competitors or opponents in negotiating research, IP, and licensing deals.

This follows from the misapprehension that we are dealing with a billion-dollar IP, but in the vast majority of cases, we are not. In fact, the evidence suggests that the vast majority of knowledge exchange and transfer takes place through channels other than IP, commercialization, and startups.

The work by Coates-Ulrichsen (2014) examined the flow of revenues from industry to universities in the United Kingdom. The author found that the knowledge exchange mechanisms match the knowledge exchange channels (see Figure 6.23) because the KEM is used as the basis for the metrics.

The following points are also noteworthy:

- Despite the policy-level obsession with IP and commercialization, this area actually generates the least revenue and, by extension, the least value of all the knowledge exchange channels. This suggests that people have been fighting furiously over the crumbs without appreciating the pie.
- Over half (57%) of the revenue that flows from industry to universities comes through contracts and collaborative research. Any economic rationalist would conclude that industry sees the real value of university engagement in the area of research rather than research commercialization.
- Consultancy and professional education generate 31% of the revenue. Almost one-third of the revenue flows from access to knowledge, expertise, and know-how in contrast to the codified knowledge/IP model.
- The use of university equipment and facilities by industry generates twice as much revenue as IP commercialization.

Essentially, the relationship between universities and industry in terms of transferring and translating knowledge is much more nuanced than considered thus far. More value is translated through know-how, expertise, and collaborative thinking than has been recognized in the past. This should inform policy discussions on the university/industry interface, encouraging these rather than seeking to regulate IP matters.

Nonetheless, university IP is incredibly important. Groundbreaking research in universities has led to inventions and technologies that can and have changed the world. However, these are special cases, rather than norms. This does not mean that we recommend a low focus on IP in universities. It is a critical part of the overall knowledge exchange system and usually the most formal part that can create enormous impact and value.

The issue has been the drift toward treating all IP as if it is hugely valuable, when the statistics show that it is not. We need different approaches and strategies to maximize the deployment of different types of IP. The tech transfer profession aims to shepherd as many technologies as possible from the lab to the market and see them change the world. However, treating all IP as world-changing IP is ultimately self-defeating. Rather, maximizing the use of IP in industry and the economy is the most sensible approach.

Do maximize the numbers of actual and potential research users. As already described, the effective use of university research to develop the economy requires research users who can actually deploy the inventions and technologies. Insufficient effort is directed toward the development of qualifying and curating these users as the ultimate creators of impact. Whether these are startups, multinational licensees, local SMEs, government agencies, students, or entrepreneurs, universities need as many partners and research users as possible.

Every successful innovation ecosystem includes an excellent research university within a dynamic entrepreneurial ecosystem. Here, we use entrepreneurial in its broadest sense, defining a community that actively seeks to pull technology from the university. In many cases, universities seek to push their inventions and technologies toward the market, whereas the most effective systems are defined by market-pulling technologies.

Hence, creating a community of well-informed, qualified research users, working with the research community to develop promising technologies seems like a logical approach. Developing this community can take many forms. However, there is a danger that given the numerous potential user groups, the effort is diluted to the extent that no significant progress is made. This community can be divided into three broad classes:

- Those uninterested in innovation: This category typically includes the majority of businesses in any economy. Such firms are going about their business as they have for years and not seeking change.
- Those interested in innovation: This category comprises businesses that think that innovation could help them perform better, be more competitive, or grow.
- Those engaged in innovation: This category includes those businesses that already work with innovation agencies and universities and that see R&D as an essential part of their business model.

From a university perspective, the first group is of little interest unless they can be promoted from uninterested to interested in innovation—this is a marketing challenge rather than a technology challenge. Vision 2030 is an excellent example of how a national movement can open up possibilities not previously considered by entrepreneurs and companies. Here, the responsibility of addressing that dawning interest falls on universities and others.

The third group is extremely important. However, from an economic development perspective, this group has limited potential, as those engaged in innovation already understand research and IP and can work with universities. Here, the challenge is to reduce the financial and bureaucratic workload to maximize the flow of knowledge to research users.

The second group is of the utmost importance in terms of economic development. With an interest in innovation, they are the key customer group for the knowledge that universities produce (IP and know-how). Identifying, training, and providing qualifications to this group as well as creating mechanisms by which they can engage in the innovation economy step-by-step should be an extremely high priority for creating a knowledge economy.

Do seek to make university technology as 'usable' as possible. University research often ends at the publication stage simply because this is an internationally applied metric for research quality. As previously stated, every researcher wants their research to make a difference, and universities should therefore be creating mechanisms to make that happen.

The gap between university laboratory research and industrially relevant technology is well recognized (sometimes called the valley of death). This is where we must take early-stage technology to a place that can elicit interest and investment from industry and markets. Many countries have formulated schemes, mechanisms, and programs to address this gap, including Small Business Innovation Research in the United States and Catapult in the United Kingdom. However, most such activities seem to operate separately from the core academic efforts of the university. Ideally, mechanisms should exist to encourage, fund, and reward the research areas that create a demonstrable impact. KAUST has set up a funding stream for this, as described later.

Do reduce the barriers to engagement between universities and industry. As previously stated, the interface between academia and industry appears to be becoming more rather than less difficult. The focus on IP and value capture seems to have obscured the value of knowledge exchange and aligned commercial and reputational values.

We may have heard of cases where an industry partner wanted to discuss a potential project, but the university first required a confidentiality agreement and then a lawyer to attend the meeting. This is not how dynamic innovative relationships work. These confidentiality and legal elements are seldom demanded by academics but are the consequence of universities' fear of missing out (on a lottery ticket win).

Instead, universities should help their researchers and research users engage in a regular, simple, and bureaucracy-free manner to the extent possible. Experience shows that if something 'valuable' does come up, then both parties will seek to reach an agreement to manage it. Trying to do so at the beginning, particularly with an 'innovation-interested' party as described before, is likely to kill the relationship before it has a chance to develop.

KAUST-specific programs

KAUST has formulated specific programs to address the recommendations above. These programs should apply to the development of the hydrogen economy in the Kingdom and the region.

1 **Research translation**
Recognizing the need to make technologies more usable and the lack of product development/proof of concept support, KAUST has introduced a \$25-million/year program to help technologies reach the marketplace. Specifically targeted at moving technologies from TRL1 to TRL6, the stage at which industry can credibly invest, as well as scaling technologies from grams to tons, the program has funded a wide range of projects.

2 **Technology Transfer**
Universities often quote the number of invention disclosures, number of patents filed, and number of patents granted as evidence of their innovation. However, while these are good outcomes, the use of technology is a key. A granted patent that does not have a use has limited value. Thus, since 2019, KAUST has switched its focus from patent filing to patent licensing. It has moved toward the deployment of technology rather than its protection. In 2018, KAUST completed 15 license deals. In 2018/2019, it completed another 16 and has continued to grow the deal pipeline at 27 (2019/2020), 41 (2020/2021), and 63 (2021/2020). This is part of the philosophy of acquiring knowledge and IP and placing them in the hands of people who can use them to create impact.

3 **Entrepreneurship**
As already stated, the research user community is vital for creating impact. Entrepreneurs are a primary category of these users, and economies stagnate without them. KAUST trains 3,500 entrepreneurs per year[2] and has partnerships with around 20 other universities across the Kingdom. These universities send their students to KAUST for experiential learning experiences around innovation and entrepreneurship. This is part of the strategy for creating deep-tech innovation and technology users in the future. KAUST cannot expect or wait for others to develop these users, so it is developing them itself. It recognizes that the journey from an undergraduate being exposed to entrepreneurship for the first time to a technology entrepreneur who can drive a deep-tech company is a long one. However, the journey has to begin someplace and the guide has to come from somewhere.

Its flagship accelerator, Taqadam, in which KAUST partners with SABB, is an excellent example of a developing program. From relatively small beginnings, the entrepreneurship team at KAUST has developed Taqadam into the premier accelerator in the region, attracting hundreds of applicants per cohort from within the Kingdom and internationally. KAUST has also created a judging panel of over 30 investors, again local and international, to ensure that the feedback given to companies is commercially and market-relevant. In 2020, the Taqadam showcase at KAUST attracted 1,100 people who came to see the final pitches in an auditorium for 1,000 people, again demonstrating the Kingdom's appetite for such technology and innovation activities. In 2021, during the COVID-19 pandemic, KAUST's showcases and pitches went online. Over 7,000 people logged in for each session. KAUST is now reaching people in the Kingdom on a scale never seen before, suggesting that there is a massive audience to address and community to engage. In addition to the entrepreneurial buzz created by this activity, KAUST is developing a pipeline of strong technology companies in the market and raising significant investment rounds.

KAUST does not set out to create unicorns; it aims to create deep-tech startups built on excellent technology that clearly understand the market that they are seeking to address (i.e., where impact comes from). Unicorns will follow the initial impact. However, universities are not in the business of creating unicorns, but rather translating excellent science into innovations that make a difference in the world. Entrepreneurs are an essential conduit of this.

4 SME Program

One objective of Vision 2030 is to increase the contribution of SMEs to GDP from 20% to 35%. While this is an ambitious objective, the equivalent contribution in other developed economies is 50%–75%. Hence, 35% does not seem to be unobtainable. However, this increase can only be achieved by moving SMEs up the value chain. In line with the aim to maximize the number of research users, KAUST surveyed SMEs in the Kingdom in partnership with the Jeddah Chamber of Commerce, Monsha'at, and Prince Mohammed bin Salman bin Abdulaziz Foundation (MISK). This was the first university-led SME survey in Saudi Arabia, to the best of our knowledge. Over 500 SMEs responded, and 90% said that they would like to innovate. When asked what would enable that, the vast majority mentioned access to talent, expertise, and facilities, consistent with our previous discussion on knowledge exchange channels. Moreover, the SMEs were not looking for deep-tech research or university IP but rather access to knowledge and capabilities.

Based on these results, KAUST is developing an SME capacity-building program to take these SMEs through the innovation value chain, as they will eventually become research partners and users that will create the impact discussed above. To date, KAUST has trained over 1,200 SMEs on innovation and technology. Further, it is developing deeper relationships with these SMEs, as they come to understand the value that the university can offer in terms of talent, knowledge, expertise, and ultimately technology-led competitive advantage.

5 **Massive Open Online Course (MOOC)**
Similarly, Saudi entrepreneurs will drive the innovation ecosystem in the future, as entrepreneurs drive ecosystems globally. Universities must provide the resources to help create those generations of entrepreneurs and innovators. KAUST conducted its first MOOC in the innovation space, an online course delivered in Arabic and aimed at potential innovators and entrepreneurs. Launched in June 2021 and supported by Amin AlNasr (Saudi Aramco), Lubna AlOlayan (SABB Bank), and Andrew Liveris (Lucid Motors), the original target was to register 10,000 young Saudis for the course in the first year. In the first month, over 71,000 signed up and the number is now over 100,000, with participation and completion rates among the best for any MOOC platform. This demonstrates the appetite for innovation and entrepreneurship in the Kingdom and creates an enormous community of innovators with KAUST at its core. This will make an enormous contribution to the entire ecosystem by 2030, as more young people learn about innovation and S&T as well as make life decisions that will take them on the technology, innovation, and impact journey.

6 **Investment fund**
KAUST Innovation Ventures is an $8-million-per-year fund that supports founders and funds early-stage deep-tech startups working to solve our most pressing S&T challenges. At present, we have 30 active startups. The fund is aiming to grow an innovation and technology investment community and attract international investors and venture capitalists to the emerging Saudi technology ecosystem. KAUST will become the long-term strategic partners of these ventures through seed-to-early stage investments. The fund has a substantial portfolio investment, with a key indicator being that co-investment ($55 million) in the portfolio surpassed KAUST's own investment ($37 million) in 2022. Having a third party invest in your technology is more difficult but also lends a degree of credibility to the company, which helps hugely with future fundraising. As mentioned above, KAUST has created a powerful network of Saudi and international investors to supply these co-investments.

7 **Research & Technology Park**
KAUST's Research & Technology Park has been viewed as a natural home for S&T companies in the Kingdom. With Aramco, Dow, and SABIC as the initial tenants, the park has become a locus for a wide range of companies. The Research & Technology Park attracts deep-tech companies to Saudi Arabia. Working in the Kingdom provides access to the largest and most rapidly developing economy in the region. Furthermore, it offers access to capital (investment funds described above), talent (the university and entrepreneurial ecosystem), knowledge (KAUST research), technology (KAUST core labs), and quality of life. From 40 tenants in 2018, KAUST now has 97 tenants, ranging from global companies to spin-ins and SMEs to very small, entrepreneur-led startups. This is the mix required to create an innovative ecosystem. Parks that have only large

companies and parks that have only startups will always be limited, as an ecosystem requires a diversity of lifeforms.

In addition, KAUST has conducted pilot-scale product development and manufacturing in areas as diverse as desert agriculture, algae production, solar energy, and desalination, with 3 million square meters of land for development. Hence, it is already becoming the pillar of deep-tech in the Saudi economy. It can provide knowledge, talent, capital, capabilities, and an innovation ecosystem. The most important deep-tech areas, given KAUST's founding research themes of food, water, energy, and the environment, will relate to the hydrogen economy, the carbon circular economy, marine sustainability, and sustainable energy. KAUST will be an enabler, a partner, and a key player in transferring its world-leading research to people who will use it to create impact.

Conclusion

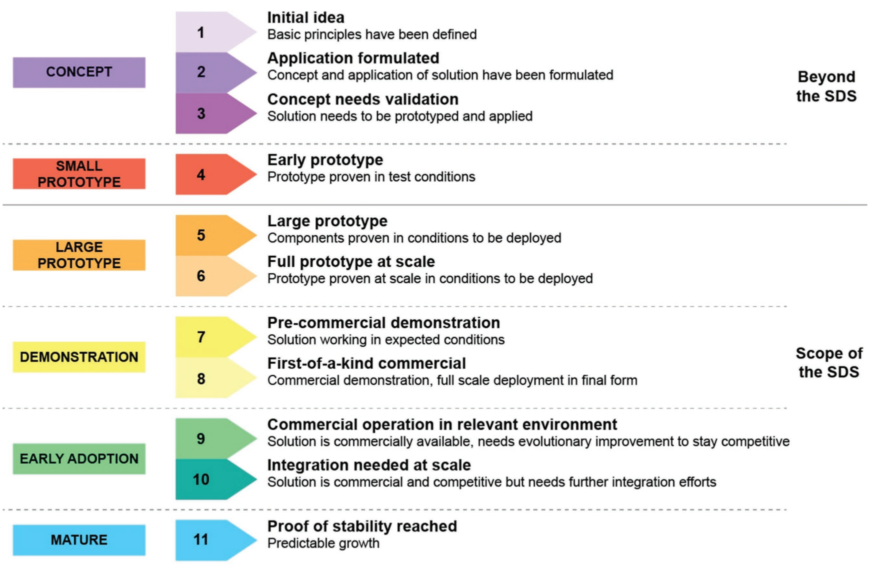
Hydrogen encompasses many technological topics and is deeply connected to several technical fields and sectors. Only a few technologies in the hydrogen domain have reached full-scale commercialization, and strategic RDDI investments are critical to developing proven and reliable hydrogen-based energy systems. This RDDI is intended to reduce levelized cost of hydrogen and improve energy conversion efficiency across hydrogen and hydrogen derivatives and associated technologies (e.g., CCUS). Supply chains are necessary in addition to building economies of scale, which, for climate technologies, are often high risk with low commercial viability.

This chapter examines global R&D and innovation in the hydrogen value chain. It elucidates the funding status of the public, private, and venture capital used for furthering hydrogen technologies. It proposes a symbiotic relationship between government departments that manage RDDI portfolios and national universities, research labs, and other research centers as well as with industry to recognize and respond to their needs. Public funding will initially unlock private capital investments in hydrogen technologies. However, global cooperation, technology sharing, and the dissemination of climate technologies are essential. In Saudi Arabia, the anticipated financing for hydrogen R&D must be based on the expected revenue goals, proportion of home-grown to imported technologies, and cost of broader innovation ecosystem development, which requires comprehensive study.

This chapter also focuses on critical technological gaps in the commercial-scale penetration of hydrogen in industries and recommends RDDI strategies for essential technologies. The faster adaptation of new technologies in the industry is a critical factor in determining the effectiveness of innovation ecosystems. Further, promising technologies that best suit Saudi Arabia's climate goals, industrial priorities, and economic objectives are listed. Hence, the chapter offers a practical guide for policymakers and research institutions to target funding in selected research innovation areas and develop a competent infrastructure. A roadmap for Saudi Arabia's hydrogen RDDI is presented, which identifies four categories of technology infusions into the economy: (1) basic research and technology translation, (2) corporate or firm research, (3) technology acquisition, and (4) technology licensing.

This chapter emphasizes the need to nurture a robust innovation ecosystem in Saudi Arabia to disseminate and deploy hydrogen technologies to achieve national priorities. Such an ecosystem is technology-agnostic, but a basic need for building a knowledge-based economy. The current RDDI ecosystem is not on par with those of global economies, which are highly innovative. Moreover, key innovation matrices such as GERD/per capita GDP and researchers per million population are low. On the GII and World Competitive Ranking, Saudi Arabia lags behind its peers in high-income economies owing to its inability to translate innovation investment into economic impact. Hence, Saudi Arabia must take steps to bridge this gap via its new RDIA initiative. Finally, a KEM—as a plausible path from academic research to industrial deployment in the Kingdom—is presented and discussed. This model links R&D with innovation through the technology transition process.

Appendix 1: TRL scale.
***Source:* IEA (2020b).**
SDS: sustainable development scenario



Notes

1 An explanation of the RDDI ecosystem is necessary here. R&D is often the first step of innovation and entails basic and applied research in universities, research institutions, and firms by scientists and engineers. This R&D stage, which is also referred to as the invention stage, is followed by the large-scale demonstration (D) of technology. Venture capital's role starts after the R&D component is de-risked and therefore better suited to the innovation (I) stage. Innovation has a broader connotation in that it includes all the steps leading to market success and new products and services and has a significant role for entrepreneurs, business managers, and industrialists. Technology transfer from universities to industry is one of the crucial links connecting R&D and innovation.

2 Given that it has approximately 1,600 students, it is evident that KAUST is training people from outside the institution as well.

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PART 2

The clean hydrogen economy and Saudi Arabia

International opportunities and challenges

7

HYDROGEN INVESTMENT

Carving out a competitive position for the MENA region in the energy transition

Wa'el Almazeedi

Introduction

The global energy supply chain is undergoing a major transition toward zero-carbon energy resources. The transition has been accelerated by the commitment of 198 countries to the legally binding 2015 Paris Agreement, an international climate change treaty reached at the twenty-first Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC). The Agreement calls for limiting global warming to below 2°C above pre-industrial levels by the end of this century and pursuing efforts to limit it to below 1.5°C.

By the end of 2016, all countries in the Middle East and North Africa (MENA) region became parties to the Paris Agreement. Except for three countries (Iran, Libya, and Yemen), the MENA countries proceeded to ratify the Agreement shortly thereafter. As of the end of 2021, over 140 countries have pledged or are considering committing to net-zero carbon emissions (Climate Action Tracker 2021a). Each country's pledge will be backed by plans and measures under enhanced Nationally Determined Contributions (NDCs) updated every five years and submitted to the UNFCCC Secretariat.

Under the UNFCCC-sponsored Race to Zero Campaign (UNFCCC 2021), 1,049 cities, 67 regions, 5,235 companies, 441 institutional investors, and 1,039 higher education institutions have pledged to net-zero emission targets by 2050. Net-zero emissions are defined as the achievement of a state in which an entity removes as much greenhouse gas (GHG) emissions from the atmosphere as it generates. Although still lacking in scope, architecture, and transparency, these targets will guide countries, cities, regions, and companies in implementing proposed actions aligned with the Paris Agreement.

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Within the MENA region, only five countries have thus far pledged to reduce their carbon emissions to zero. The United Arab Emirates (UAE) and Israel have pledged to attain net-zero emissions by 2050, Turkey by 2053, and Bahrain and the Kingdom of Saudi Arabia by 2060. Saudi Aramco has pledged to reach its target by 2050 (Energy and Climate Intelligence Unit 2021; Net Zero Tracker 2021). Despite these ambitious announcements, MENA countries' response to the energy transition has been slow. A World Bank (2020) report identified MENA countries as among those most poorly prepared for the low-carbon energy transition.

Similarly, the Massachusetts Institute of Technology (MIT) placed all MENA countries (except for Morocco) into the two lowest-rated categories of its 2022 Green Future Index (MIT Technology Review Insights 2022). Specifically, the report stated that MENA countries are "making slow and uneven progress" and "will be left behind in the green future." Even without a net-zero target, Morocco was the only MENA country whose actions to meet its Paris Agreement commitments were rated "Almost Sufficient" (Climate Action Tracker 2021b).

The hydrogen opportunity

MENA countries' investments in renewable and low-carbon hydrogen may prove to be the most cost-effective response to the energy transition and compensate for lost time. It may be the only way for MENA oil and gas-producing countries to avoid the high risk of rendering a sizable proportion of their hydrocarbon reserves stranded. Market entry into the emerging hydrogen supply chain can reduce reliance on hydrocarbons and public expenditure as the main drivers of economic growth. It may also allow MENA countries that lack hydrocarbon resources to replace growing fuel and ammonia imports, thereby improving fiscal balances and enhancing energy security. In summary, hydrogen investments provide MENA countries with a compelling value proposition (Table 7.1).

The energy transition holds a silver lining for MENA countries. As the most efficient energy carrier, renewable electricity has been spearheading the energy transition. However, on its own, it is not sufficient to decarbonize hard-to-abate sectors such as heavy industry, heavy-duty transportation, aviation, and shipping. Moreover, alone, it cannot facilitate its integration into the heating, industry, transportation, and natural gas sectors, referred to as "sector coupling." Both clean molecules and electrons are required to attain the Paris Agreement carbon emissions reduction targets. Renewable electrolytic hydrogen and low-carbon fossil hydrogen, termed green and blue hydrogen, respectively, can achieve both objectives, either independently or via carriers such as ammonia. Hence, they can complement the role of electricity in the energy transition.

Blue hydrogen is produced by reforming oil, gas, and coal resources but with carbon dioxide (CO_2) emissions captured and stored underground or consumed in other processes. Therefore, blue hydrogen presents a window of opportunity during the transition to green hydrogen, which is produced by electrolyzing water using

TABLE 7.1 Hydrogen's value proposition for the Middle East and North Africa region

✓ Supply low-carbon or carbon-neutral energy products to end-use energy consumers globally, thereby reducing the aggregate carbon footprint of energy exports.
✓ Substantially scale up installed renewable energy capacity.
✓ Incentivize investments in carbon capture, utilization and storage (CCUS) infrastructure and scale up the use of captured carbon dioxide (CO_2) in enhanced oil recovery (EOR) to:

- Maximize oil reserve recovery.
- Extend the life of oilfields.
- Attain (potential) carbon neutrality for petroleum exports (provided a disproportionate amount of CO_2 is injected for every barrel of oil recovered).
- Maintain minimum investments in oil and gas reserves and the associated infrastructure to enable a smooth energy transition.
- Drive the creation of the circular carbon economy (CCE).

✓ Carve out a proactive role in the ongoing energy transition and join countries that have announced and devised measures to attain net-zero emissions targets.
✓ Transform the private sector's role in the national and regional economy and create world-class companies that can compete globally (e.g., ACWA Power, OCI, and Gulf Cryo).
✓ Create job opportunities in the emerging hydrogen and CCUS supply chains.

Source: Author.

solar or wind electricity. Turquoise hydrogen, produced by the pyrolysis of natural gas, also offers a parallel track for oil and gas producers. Specifically, the technology does not emit CO_2 but produces carbon black as a by-product. In the remainder of this chapter, green hydrogen is referred to as "renewable" hydrogen, whereas blue and turquoise hydrogen are termed "low-carbon" hydrogen.

By 2050, the value of the hydrogen market is expected to reach $1.0–$2.2 trillion (up from $117 billion today) and account for 16% of the world's energy needs (Barclays Capital (2020), Bank of America (2020), Goldman Sachs (2020), Hydrogen Council (2020). However, to fulfill hydrogen's decarbonization role, an annual production volume of 660 mt by 2050, or 22% of final global energy demand, is necessary (Hydrogen Council and McKinsey & Company 2021a). First, this will require 3–4 TW of electrolysis capacity and 4.5–6.5 TW of renewable energy generation capacity. Second, it will demand 140–280 mt of natural gas reforming capacity for low-carbon hydrogen production coupled with the infrastructure to store 1–2.5 Gt of CO_2.

In 2021, the International Energy Agency (IEA) estimated that hydrogen demand reached 94 mt, most of which was used in the refining and fertilizer industries. In the same year, Middle Eastern countries consumed 12 mt of hydrogen, the third largest consumer globally after China and the United States. Of this, 45%, 36%, and 14% were used in the fertilizer, refining, and steel industries, respectively. This proportion represents approximately 10% of global hydrogen demand, including by-product hydrogen production. Natural gas, accounting for 90%, is the predominant hydrogen production feedstock in the Middle East and worldwide (IEA 2021a, 2022; Qamar Energy and Netherlands Enterprise Agency 2020). As an industry feedstock and a low-carbon energy vector, hydrogen demand, based on IEA and International Renewable Energy Agency (IRENA) estimates, will reach 528–614 mt/y by 2050.

Within the MENA region, hydrogen demand is expected to reach 25–50 mt/y by 2050 in Gulf Cooperation Council (GCC) countries alone (Roland Berger and MENA Hydrogen Alliance 2021). This new demand will be fueled by renewable and low-carbon ammonia and methanol production and local hydrogen consumption in new transportation and energy applications. However, MENA countries' exports are likely to outpace local demand by a wide margin, at least initially.

China, the European Union (EU), North America, and South and East Asia are projected to become the markets with the largest demand. In particular, China is expected to become self-sufficient. North America will become both exporter and importer, satisfying supply shortfalls from South American producers such as Chile, Brazil, Uruguay, and Argentina. Hence, MENA countries are well positioned to capture a significant demand share in the EU and South and East Asian markets (Qamar Energy and Netherlands Enterprise Agency 2020).

The EU is projected to import between 30 mt/y and 60 mt/y of renewable or low-carbon hydrogen by 2050 (World Energy Council 2022). In its efforts to reduce EU's reliance on oil and gas imports, the European Commission announced the RePowerEU strategy calling for a target of 20 million t/y of renewable hydrogen production by 2030, of which 50% would be imported (Helena Uhde 2022). Furthermore, according to Japan's Ministry of Economy Trade and Industry (METI) and the Hydrogen Council, Japan and South Korea will import 35 mt/y of renewable or low-carbon hydrogen and a further 30 mt/y of ammonia by 2050. The uncertainty about potential import requirements is driven by several factors. It may be cheaper to produce low-carbon hydrogen domestically than to import it. Conversely, some countries such as Japan and South Korea have limited access to CO_2 storage capacity and/or renewable energy resources. To mitigate this problem, production pathways such as the pyrolysis of liquefied natural gas (LNG) are being considered.

Therefore, MENA countries could have substantial hydrogen opportunities. GCC countries dedicating a large proportion of installed renewable electricity capacity to electrolysis could together capture 10%–30% of the European and East Asian market share (Roland Berger and MENA Hydrogen Alliance 2021). In aggregate, this could generate annual revenues of $70–$200 billion for the region's countries.

In addition, the demand for low-carbon fuels in the shipping and aviation industries presents a substantial opportunity for MENA countries. Renewable and low-carbon ammonia may become the preferred bunker fuel for the shipping industry, as it moves aggressively to reduce its carbon footprint. Meanwhile, synthetic kerosene (e-kerosene) may play a critical role in decarbonizing global aviation.

MENA hydrogen export potential: a reality check

Cross-border hydrogen trade could reach 50 mt/y and 132 mt/y by 2030 and 2050, respectively, based on the IEA's (2021b) global demand and IRENA (2022c) cross-border trade projections. A significant proportion of the traded hydrogen is expected to be transported as ammonia. Ammonia is an energy vector in its own right and may not need to be reconverted into hydrogen at the receiving port.

MENA exporters would compete with Australia, Brazil, Canada, Chile, and Russia to supply around 102 mt/y of imports by the EU and Asian markets in 2050. MENA exports could capture up to 60 mt/y or around 58% of imports, representing approximately 11% of global demand. Exports would comprise both renewable and low-carbon hydrogen, with MENA capturing the lion's share of the latter (Table 7.2). By adjusting for capacity and energy conversion factors, exports would require: (a) 96 mt/y of natural gas reforming capacity coupled with the infrastructure to store 0.3 Gt/y of CO_2 and (b) 232 GW of electrolysis capacity and at least 490 GW of renewable generation capacity.

TABLE 7.2 Middle East and North Africa's hydrogen export potential

	2030	*2050*
Global hydrogen demand forecast (mt/y)	200	530
Cross-border hydrogen trade (mt/y)	50	132
Net global hydrogen imports (mt/y)	40	103
Potential MENA hydrogen exports (mt/y)	21	60
Energy content (EJ/y)	2.5	7.2
Low-carbon hydrogen requirements		
Methane volume (mt/y)	48	96
Carbon dioxide (CO_2) storage (mt/y)	150	300
Renewable hydrogen requirements	51	197
Electrolysis capacity (GW)	107	414
Solar photovoltaic (PV) and wind capacity (GW)		
Capital investment requirements		
Reforming capacity (US $ billion)	48	96
Electrolysis (US $ billion)	35	79
Solar PV and wind (US $ billion)	109	419

Assumptions: *Hydrogen demand: IEA net-zero emissions scenario for global hydrogen demand. Cross-border trade: IRENA (2022c) for hydrogen cross-border trade. MENA export: Based on cross-border trade less regional pipeline trade, add back the amount captured by potential North African pipeline exports to the EU, discount local consumption to zero. Infrastructure requirements: 40/60 renewable energy/fossil (2030), 60/40 renewable energy/fossil (2050), 90% capacity factors (steam methane reforming (SMR)/and autothermal reforming), 11 kg CO_2/kg of hydrogen. Energy content (lower heating value, LHV): 120.5 MJ/kg of hydrogen, 42 MJ/kg of crude oil, 45 MJ/kg of LNG. 70% load factor (electrolyzer), 30%/40% capacity factors (photovoltaic (PV)/wind) assuming energy storage and hybridization and learning curve-associated efficiency improvements after 2030. CAPEX: $857/kW (solar PV), $1,325/kW (wind), $2,950/ton for 350,000 t/y SMR + carbon capture not including ammonia (NH_3) synthesis loop, $400–$680/kW (alkaline electrolysis (AEL)/ polymer electrolyte membrane (PEM)).*

Source: Author's MENA Hydrogen Export Model.

The latter requirement presents three challenges. First, the renewable generation capacity required for electrolysis is a nearly 35-fold increase over MENA's installed non-hydro renewable capacity of 14 GW in 2021. Barring Central America, MENA's renewable energy penetration is the lowest worldwide—approximately 4% of total installed capacity and less than 1.5% of global installed non-hydro renewable capacity (IRENA 2022d). Second, renewable capacity may have to be dedicated exclusively to electrolysis and not diverted from the grid to satisfy major demand center regulators' additionality requirements. This would ensure that the energy supply chain is decarbonized in the most energy-efficient manner possible. Additionality is a likely ingredient of hydrogen certification and a condition to which exporters may need to adhere. Third, hydrogen producers may find themselves competing for low-carbon electricity with electricity-hungry crypto mining centers. Certain MENA countries have recently been targeted by crypto mining companies as a potential source of low-cost electricity. Indeed, some MENA countries have already instituted favorable regulatory frameworks for virtual assets to attract crypto miners and trading platforms (S&P Global 2022b). Moreover, the crypto mining industry is under tremendous pressure to reduce the carbon footprint of its operations due to its growing energy consumption.

On an energy-equivalency basis, MENA hydrogen exports in 2050 would be 7.2 Exajoule (EJ), only slightly surpassing 2021 LNG exports, estimated to be 112 mt/y, equivalent to 5 EJ/y. This pales in comparison with the region's 2021 crude oil exports of 1,321 mt/y, equivalent to 56 EJ/y.

International hydrogen collaboration and procurement

Major industrialized countries have encouraged MENA nations to capitalize on their cheap hydrogen production potential. Germany and Japan have created clear momentum for international engagement in their national hydrogen strategies and roadmaps with low-cost hydrogen producers in developing and emerging markets. This engagement includes incentives ranging from discretionary funding for pilot projects and feasibility studies to joint research programs. Despite these constructive developments, this engagement comes with strings attached. Most of the proposed projects are export-oriented and subject to the evolving regulatory frameworks of the destination markets in question. Moreover, the proposed projects are contingent on the involvement of certain project developers, original equipment manufacturers, and service providers. They may not facilitate local private sector participation or local ecosystem development, which are needed for MENA countries to create a competitive advantage in the emerging hydrogen value chain.

However, one welcomed development is the launch of global hydrogen procurement programs by both Germany and Japan. Although not specifically directed at the MENA region, Germany's **H2Global** program may have a far-reaching impact. The program's double auction-based mechanism finances renewable hydrogen imports by competitively procuring long-term supply contracts globally and matching them with aggregated short-term offtake contracts locally. It compensates off-takers for the price difference using "contract for difference" subsidies (H2Global 2022). The success of H2Global could mainstream its procurement program across the EU. Similarly in Japan, **JERA**, an alliance of two electric utilities and the world's largest LNG trader, launched an international competitive bid in early 2022 to procure up to 500,000 mt/y of low-carbon ammonia for delivery in 2027.

A new energy paradigm for MENA

Thus, prospective MENA exporters face new market realities. If they were to capitalize on the hydrogen opportunity, they would need to address the following eight strategic issues.

1 **Hydrogen is not the new oil:** Hydrogen should not be treated as an energy commodity such as natural gas, oil, or petroleum products. IRENA (2020c) highlights that unlike oil and gas, hydrogen is a conversion and not an extraction business and can potentially be produced competitively globally via electrolysis. This alone will change how hydrogen and its derivatives are traded. IRENA estimates that by 2050, only approximately 25% of global hydrogen demand will be met by cross-border trade, with the bulk produced and consumed domestically. By comparison, cross-border trade for LNG is slightly higher at 33%, whereas that for crude oil comprises 74% of global demand. Hence, MENA exporters' participation in import market hydrogen supply chains will be critical for capturing a hydrogen market share comparable to their current oil and gas share.

Despite retaining some features of LNG, value in the renewable and low-carbon hydrogen supply chains will be created closer to end-use customers and driven by three factors (Figure 7.1):

- Acting mainly as a complement, the hydrogen value chain will be linked more closely to that of electricity.
- End users will play an equal, if not larger, role to that of other stakeholders whereby hydrogen use cases would send price and quality signals to producers that would need to adapt to evolving market requirements.
- Most regulators in end-use markets will emphasize inclusiveness and equity across the energy value chain, preventing producers from retaining a disproportionate amount of value. Therefore, cost competition may not be a sufficient strategy driver.

2 **Time to market:** Market entry should be expedited along three interrelated fronts:

a The handful of markets likely to experience chronic supply shortfalls, such as the EU, Japan, and South Korea, should be targeted first. Furthermore, MENA exporters should be prepared to compete on price with other equally if not better endowed and cost-competitive suppliers such as Chile and Australia.

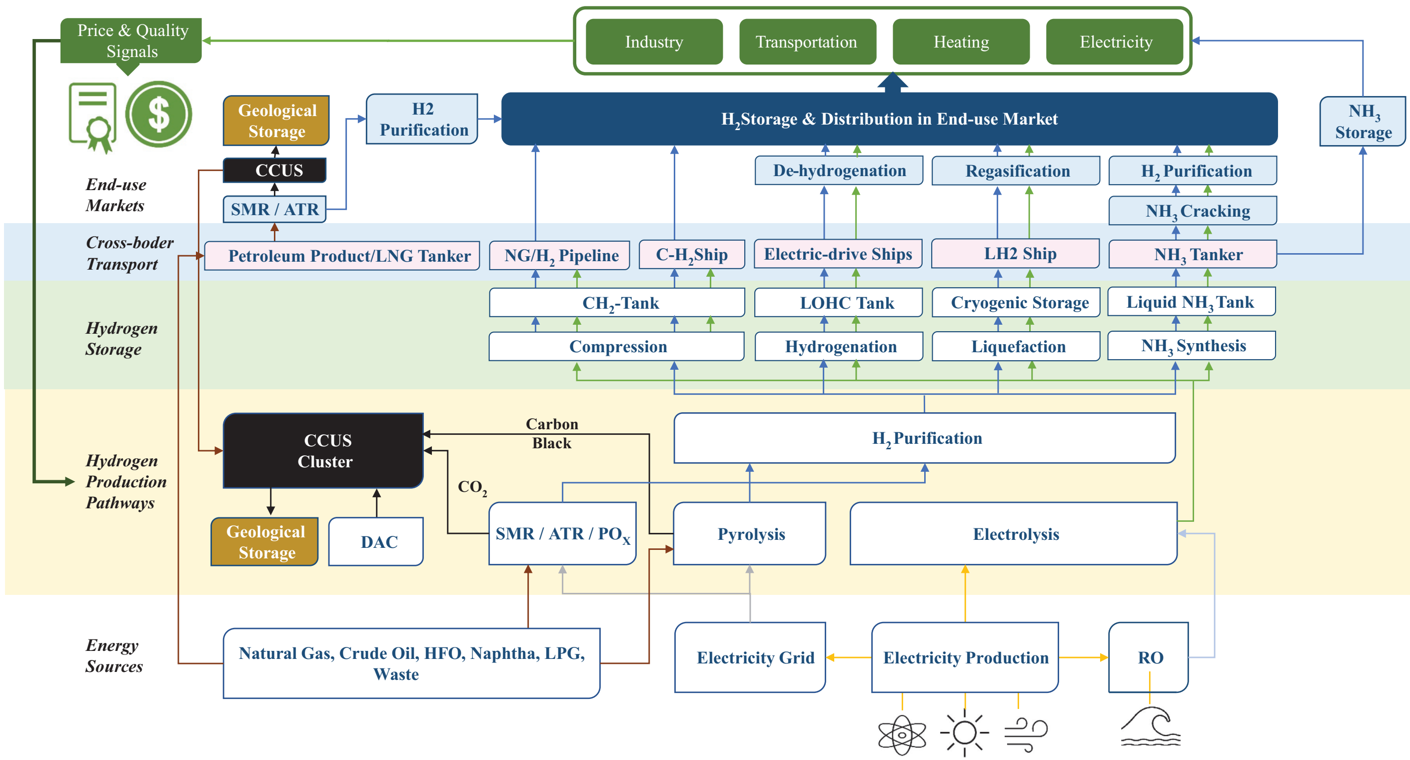

FIGURE 7.1 The evolving end-use-centered hydrogen supply chain.

Source: Author.

b The implementation of hydrogen strategies should be expedited. This would ensure capital investments in low-carbon hydrogen production and related carbon capture, utilization, and storage (CCUS) infrastructure do not become stranded as renewable hydrogen evolves into the default hydrogen production pathway. Objective and dynamic assessments of the narrowing levelized cost of hydrogen (LCOH) differential between renewable and low-carbon hydrogen are necessary. This would optimize capital allocation and aid the design of appropriate regulatory incentives.

c Substantial capital should be committed upfront to attain a first-mover advantage under considerable market, regulatory, and technological uncertainty both at home and overseas. Bankable projects require long-term offtake agreements to attract limited project financing. Therefore, first-of-a-kind hydrogen and derivative projects face several challenges. **First**, no merchant market for hydrogen exits at present. Currently, hydrogen serves captive industrial markets, where it is fed into industrial processes as a feedstock without third-party commercial agreements or prices. **Second**, significant commercial-scale renewable or low-carbon hydrogen production is yet to come on stream. Moreover, investment cases for hydrogen use as an energy vector in the industrial, heating, electricity, and transportation sectors are still evolving. **Third**, dedicated hydrogen (and CCUS) legislation and policy lag far behind the development of renewable and low-carbon hydrogen production. **Fourth**, a globally accepted hydrogen certification scheme would need to be developed and consistently applied across borders. This would ensure that end users can evidence the GHG and sustainability attributes of their hydrogen consumption and meet their emissions reduction targets.

3 **Renewable electricity capacity:** Significantly accelerating the rate of development of renewable electricity capacity is a prerequisite for scaling up renewable hydrogen. Low-carbon hydrogen will be unable to compete in the long term. The supply chain of renewable hydrogen is simpler, cheaper to develop, and has fewer entry barriers. It lacks an upstream component, and renewable electricity costs have historically been deflationary. The scale up of renewable hydrogen is likely to be held back not by cost but by the access to sufficient renewable electricity capacity.

4 **Local hydrogen ecosystems:** Local ecosystems and end-use applications should be developed as opposed to primarily creating an export-oriented hydrogen industry. Price and quality signals created by end-use applications and producers' ability to quickly adapt to these signals determine value creation across the hydrogen supply chain. Furthermore, local ecosystems and the incentives for their development are crucial to attracting entrepreneurs, small and medium-sized enterprises (SMEs), and private companies. All these parties would strengthen regional and national competitiveness.

5 **Incentive schemes:** Overarching regulatory frameworks for the energy sector are essential for removing entry barriers, creating a level playing field between industry stakeholders, instituting standards, and introducing incentive schemes to kickstart and scale up hydrogen production and applications. Regulation will provide a basis for allocating funds and provisioning for contingent liabilities in national budgets. This will then allow the financing of subsidies for projects and consumers (e.g., contracts for difference) and the provision of financial support to projects (e.g., grants, equity, loans, and loan guarantees). This would improve the bankability of first-of-a-kind projects. As this may take time, the first step could be to promote the development of hydrogen hubs and CCUS clusters, which would create opportunities for local and international private sector players and act as a pull factor for foreign direct investment. Proximity to industrial demand centers will lower costs, de-risk technology, and offtake and leverage the existing infrastructure.

6 **Role of the private sector:** Governments should aggressively facilitate and private industry should fiercely lobby for a proactive role of the private sector and SMEs. First, this will require creating a level playing field for them with the public sector in the energy space. Second, incentives must be provided to build and upgrade the necessary institutional capacity to enable them to become stand-alone project developers and service providers. Private companies and SMEs, rather than governments, are driving innovation in the hydrogen supply chain globally. Notable role models have already emerged in the MENA private sector, such as ACWA Power, OCI BV, and Gulf Cryo. Many more private companies would need to be established before 2030 for the MENA region to play a meaningful role in hydrogen production.

7 **Regulatory engagement:** Proactive engagement with regulators in demand centers by both MENA governments and project developers must be orchestrated at a very early stage. This would ensure that hydrogen imports are treated fairly and objectively. The impact of regulations on potential exports cannot be underestimated and needs to be addressed sooner rather than later. An example is the EU's Carbon Border Adjustment Mechanism. In the absence of a global binding agreement on carbon prices, this policy aims to reduce carbon leakage by regulating the carbon intensity of the EU's imports. Presenting persuasive science-based arguments aimed at keeping low-carbon hydrogen relevant and making a case for its inclusion in a portfolio of decarbonization options is equally important.

8 **Circular carbon economy (CCE):** Promoting and institutionalizing the CCE framework is crucial if low-carbon hydrogen is to be considered a sustainable decarbonization option. This can only be realized by developing bankable business cases and outsourcing services across the CCUS supply chain to specialized firms. It also requires structured incentive mechanisms for carbon capture and storage (CCS) (including use of captured carbon dioxide in enhanced

oil recovery [EOR]) and for carbon capture and utilization (CCU) (including production of synthesis fuels and advanced materials). The appeal of CCE to institutional investors and energy consumers may increase substantially if the captured carbon dioxide and solid carbon (produced from the pyrolysis of natural gas) are directed toward the manufacture of advanced materials, currently being or expected to be used in energy transition applications. Examples include polyacrylonitrile-based carbon fiber composites (the material of choice for compressed hydrogen fuel tanks in fuel cell electric vehicles [FCEVs]) and graphene (a two-dimensional breakthrough material earmarked for energy storage, solar energy, water desalination, and superconducting applications) (Almazeedi 2020). These mechanisms can allow developers to recoup and earn a return on the capital invested. See the section titled **Institutional capacity for hydrogen project development and financing** for more details on CCUS as well as Figure 7.2.

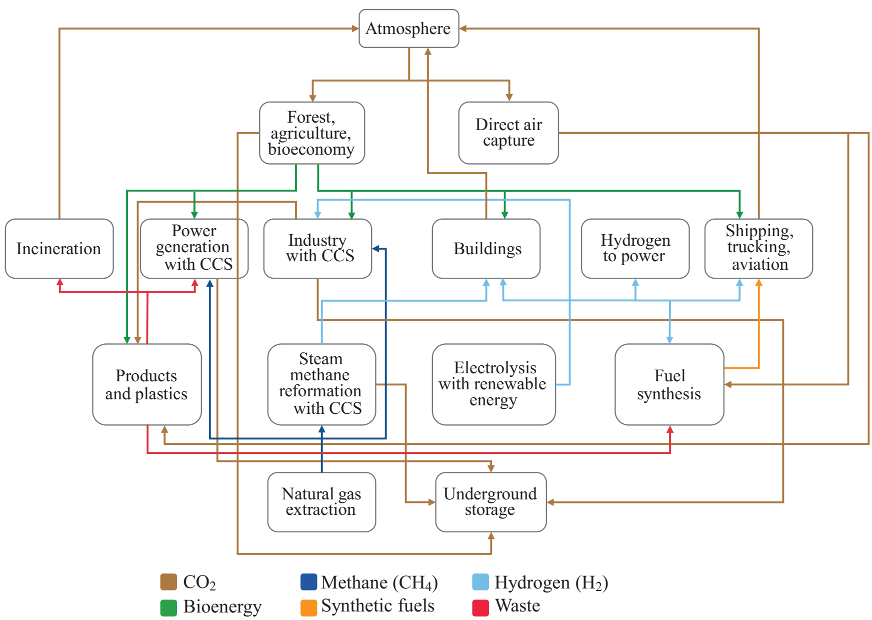

FIGURE 7.2 Circular carbon economy.

Source: Author.

MENA's competitive positioning

MENA countries possess the necessary resources to produce both low-carbon and renewable hydrogen. The IEA's (2019) report, "The Future of Hydrogen," identifies the Middle East as a region ideally positioned to produce low-carbon hydrogen cheaply at a vast scale (Table 7.3).

TABLE 7.3 Middle East and North Africa's competitive positioning in hydrogen

Low-carbon hydrogen	*Renewable hydrogen*
✓ Access to a variety of hydrocarbon feedstocks that could be allocated to hydrogen production	✓ Access to abundant renewable energy resources: solar (high solar irradiation levels) and wind (high mean power densities and wind speeds in selected MENA countries)
✓ Strong hydrogen and ammonia production and liquefied natural gas (LNG) export competencies	✓ Among the lowest levelized cost of electricity (LCOE) worldwide; record-breaking tariffs realized by independent solar photovoltaic (PV) power projects: 1.3 to 1.7 US $ cents/kWh (Table 7.4)
✓ First-of-a-kind locally articulated framework for a circular carbon economy (CCE) gaining traction globally	✓ Proven and tested public/private partnership frameworks for power project development, financing, construction, operations and maintenance, and ownership
✓ Commitment to carbon capture, utilization and storage (CCUS) and use of CO_2 for enhanced oil recovery (EOR)	✓ Emerging local world-class private power and ammonia project developers
✓ Significant carbon dioxide (CO_2) storage capacity in depleted oil and gas wells and deep saline formations	✓ Large-scale renewable hydrogen projects under development
✓ Growing competencies within the local private sector in CO_2 transportation, storage, and distribution	✓ Strong interest from major international companies in hydrogen and ammonia projects being developed in the region
✓ Strong interest from international industrial gas and oilfield service companies to invest in outsourced CCUS-related services	✓ Strong interest from international industrial gas and electrolyzer original equipment manufacturing companies
✓ Demonstration projects with hydrogen and ammonia off-takers in end-use markets	✓ International applied research collaborations on Power-to-X and synthetic fuels
✓ Access to substantial equity and debt financing capacity to be sourced from sovereign wealth funds, regional development banks, and local commercial banks	

Source: Author.

MENA resource constraints

MENA countries have uneven access to renewable energy and hydrocarbon resources and to the capital to develop them, and some experience severe water scarcity.

Renewable energy resources: Most MENA countries have access to abundant solar energy resources; however, this is not true for wind resources. Renewable hydrogen projects with access to hybrid solar/wind electricity capacity have advantages over those that primarily rely on solar energy. Combining solar photovoltaic (PV) with wind considerably increases the electrolyzer's capacity factor. Hybridization improves the electrolyzer's profitability and reduces the need to access the energy storage capacity required to mitigate the intermittency of solar and wind resources. For example, Morocco, Egypt, Oman, and some areas of Saudi Arabia have access to abundant wind resources. These countries have higher mean power densities and wind speeds than other MENA countries (Global Wind Atlas 2021). Morocco's mean power density and wind speed values are 793 W/m^2 and 8.84 m/s, respectively, whereas those of Egypt are 663 W/m^2 and 9.1 m/s, respectively. The equivalents for Oman are 614 W/m^2 and 8.5 m/s, respectively, and those of Saudi Arabia (Tabuk region) are 662 W/m^2 and 8.2 m/s, respectively. The NEOM Green Hydrogen Company project at NEOM in Saudi Arabia, powered by 4 GW of solar and wind power, is a case in point.

Natural gas resources: Natural gas is, by far, the dominant and most cost-competitive feedstock for the production of low-carbon hydrogen via steam methane reforming (SMR) and autothermal reforming. For example, Kuwait is the largest importer of LNG in the MENA region, which satisfies approximately 50% of the country's electricity requirements. It would need to identify alternative feedstocks to natural gas to develop low-carbon hydrogen or ammonia projects at scale. These could include refinery petroleum products such as liquefied petroleum gas (LPG) and naphtha for reforming and fuel oil and vacuum bottoms for partial oxidation. Notwithstanding feedstock constraints, MENA oil and gas producers must increase CCUS capacity to scale up low-carbon hydrogen production, a challenge they share with energy majors.

Water scarcity: Water is a key input for hydrogen production. MENA countries are among the most water-stressed countries worldwide. Producing hydrogen via natural gas reforming (SMR) plus CCS and electrolysis requires 5.5 and 9.0 L of desalinated water per kg of hydrogen produced, respectively. Adding steam and evaporative cooling losses for SMR plus CCS and cooling, feed water treatment and water disposal for electrolysis, water requirements would increase to a range of 18–44 and 60–95 LH_2O/kgH_2, respectively (GHD Perspectives 2021). Even if water represents approximately 2%–4% of the LCOH, this may necessitate substantial capital investments in the water supply and treatment systems, including desalination capacity. Assuming that additional investments can be funded, a proportion would need to be allocated to and reflected in the LCOH, undermining the region's competitiveness. Hydrogen certification schemes currently under development may be compelled by regulators to include sustainability metrics such as water consumption and land use, apart from production-related GHG emissions. This is to ensure that economic and social developments are not compromised. IRENA (2022b) now incorporates exclusion criteria into its LCOH methodology. This has reduced MENA's economic potential for producing electrolytic hydrogen by 84%. (See Annex 1. for seawater electrolysis.)

ANNEX 1 Middle East and North Africa's technology research, development, and demonstration roadmap

Technology	*Technology readiness level*	*Description*	*Objectives*	*Benefits to MENA*
Hydrogen storage and transportation	4–6 (liquid organic hydrogen carriers)	Efficient hydrogen carriers are hydrogen-rich liquid or solid phase materials from which hydrogen can be liberated on demand. Such carriers have high hydrogen densities at low pressure and near ambient temperature.	Reduce the levelized cost of production, transmission, dehydrogenation, and distribution.	Facilitate the storage and cross-border transportation of hydrogen and potentially capitalize on the existing fossil fuel infrastructure.
	5–7 (liquid hydrogen)	Hydrogen carriers include one-way carriers such as ammonia, methanol, and liquid hydrogen as well as two-way carriers. Of the latter, methylcyclohexane (MCH) is typically referred to as a liquid organic hydrogen carrier (LOHC).	Reduce hydrogen losses during extended storage periods.	Increase the competitiveness of hydrogen exports from MENA countries and create local demand for certain hydrogen applications.
			Liquid hydrogen does not require dehydrogenation or cracking to convert back to hydrogen.	**MENA example:** The Abu Dhabi National Oil Company (ADNOC) and Aramco-shipped low-carbon ammonia cargo to Japan and South Korea as pilots. ADNOC co-sponsored feasibility studies for ammonia (South Korea), LOHCs (EU and Japan), and liquid hydrogen (Asian trading and technology companies).

(*Continued*)

ANNEX 1 (Continued)

Technology	*Technology readiness level*	*Description*	*Objectives*	*Benefits to MENA*
	8–11 (ammonia)	Notes: This excludes hydrogen carriers with a carbon content such as LNG and methanol.	Notes: Ammonia can be used both as a hydrogen carrier and directly as a fuel or feedstock for different applications. The production of hydrogen from ammonia via catalytic cracking or plasma decomposition remains under development.	
Methane pyrolysis	3–6	The production of hydrogen via thermocatalytic decomposition at high temperatures in the absence of oxygen, producing solid carbon instead of CO_2 as a by-product. Hydrogen produced from pyrolysis is referred to as turquoise hydrogen.	Reduce the LCOH, develop improved plasma-based processes, and identify opportunities to use solid carbon to manufacture a variety of petrochemical, chemical, and advanced materials.	Eliminate the need to access a capital-intensive carbon capture, utilization and storage (CCUS) infrastructure. Pyrolysis can also be used to produce hydrogen from waste. **MENA example:** Waste-to-Hydrogen (W2H) project under development in Sharjah (UAE). See Table 7.4.
Seawater electrolysis	3	Use of seawater directly in electrolysis, bypassing the need for desalination.	Develop active, stable, and selective catalysts able to effectively split seawater without setting free ions of sodium, chlorine, and calcium, which render catalysts inactive.	Eliminate the need to divert desalination capacity to hydrogen production in high water-stress regions. Develop brine-free electrolysis processes to reduce the environmental impact on fragile marine ecosystems.

(*Continued*)

ANNEX 1 (Continued)

Technology	*Technology readiness level*	*Description*	*Objectives*	*Benefits to MENA*
Synfuels	5	Synthesis of clean fuels and chemical feedstocks from renewable or low-carbon fossil hydrogen combined with CCUS-sourced carbon dioxide (CO_2) in the presence of a catalyst is termed Fischer–Tropsch synthesis. Fuels include e-kerosene for aviation applications.	Increase electricity-to-chemical energy conversion efficiencies, as they require substantial additional renewable energy electricity capacity to offset conversion losses.	Use the existing fossil fuel infrastructure, which would otherwise become stranded over the long term.
			Notes: The round-trip conversion back to electricity has low efficiency. Therefore, storing electrical energy as chemical energy can only be justified for electricity sources that would otherwise be wasted. This underpins the Power-to-X concept based on utilizing curtailed or excess renewable energy electricity as an input.	Stepping stone to realizing the "solar refinery" concept as a replacement for conventional crude oil refining.
				<u>MENA example</u>: Industry players and research institutes from the UAE and Morocco are working with their counterparts in Germany and Japan to explore the production of synfuels, including e-kerosene (See Table 7.4).

(*Continued*)

ANNEX 1 (Continued)

Technology	*Technology readiness level*	*Description*	*Objectives*	*Benefits to MENA*
Direct air capture	6	The use of forced draft circulation to absorb atmospheric CO_2 using solvents or fixed-bed sorbents.	Reduce the cost of capture and develop efficient solvents and sorbents that can be regenerated, operate at high temperatures, and remain unaffected by atmospheric contaminants.	Provides a tool that can be readily paired with hydrogen production to offset uncaptured or residual CO_2 emissions. Under certain conditions, net-negative lifecycle GHG emissions for hydrogen production could be attained.
		Captured CO_2 can be stored permanently underground or utilized as a feedstock for a variety of applications, including synfuel production.		**MENA example:** Climeworks and 44.01 are developing a pilot project for direct air capture and CO_2 storage in peridotite rock formations in Oman.
Water cooling (electrolyzers)	N/A	Electrolyzers have significant cooling loads requiring additional 30–40 LH_2O/kgH_2 for evaporative cooling.	Evaluate alternatives to evaporative cooling (e.g., air cooling and closed loop chiller systems) to reduce water consumption and the volume of wastewater/brine.	Reduce water demand for renewable hydrogen production.
Hydrogen sulfide decomposition	N/A	Conversion of hydrogen sulfide to hydrogen (main product), water, and sulfur via decomposition methods (including catalytic, non-thermal plasma, electrochemical, and thermochemical). Natural gas is considered to be sour if it has more than 5.5 mg of hydrogen sulfide per m^3 under standard pressure and temperature.	Develop stable and low-cost catalysts capable of supporting large-scale production and separation methods and withstanding hydrogen sulfide toxicity.	The MENA region is home to some of the world's largest sour gas reserves.

(*Continued*)

ANNEX 1 (Continued)

Technology	*Technology readiness level*	*Description*	*Objectives*	*Benefits to MENA*
		Hydrogen sulfide is considered a waste-gas disposal problem, and its emissions are removed via the Clause process to produce elemental sulfur as the main product.		Hydrogen sulfide decomposition provides an opportunity to monetize ultra-sour gas reserves. It has the potential to become an economically viable hydrogen production pathway and a hedge against low LNG prices in the future. **MENA example:** The Ghasha ultra-sour gas offshore project comprising Hail, Ghasha, Dalma, and other oil, gas, and condensate fields in the UAE could be an ideal candidate.

Source: Author, supported by IEA ETP (2022c), IRENA (2022a), GHD Perspectives (2021), De Crisci, Moniri, and Xu (2018) and Harrison (2022).

Notes: TRL: Technology readiness level.

Capital costs: The cost of capital for hydrogen projects affects their competitiveness. The weighted average cost of capital (WACC) differs markedly between MENA countries. For example, Kuwait, Saudi Arabia, and the UAE have lower WACCs than the other MENA countries. Key competitors such as Australia and Chile command even lower WACCs. Lack of transparency over capital costs will prevent MENA countries not only from applying appropriate discount rates to hydrogen projects but also from designing fit-for-purpose policy incentives. The impact would be larger for first-of-a-kind hydrogen projects, where low-cost debt may be replaced with higher cost equity, driving up the WACC and thereby worsening the LCOH.

Export market competitiveness

MENA countries are well positioned to produce renewable and low-carbon hydrogen at a lower LCOH than the target demand centers in the EU and East Asia. In fact, given a sufficiently low cost of shipping hydrogen to these centers, hydrogen imports could compete with local production. The Hydrogen Council and McKinsey & Company (2021b) estimates that shipping costs using selected hydrogen carriers would add \$0.3–\$1.2/kg to production costs by 2030. If ammonia were used, the cost would be at the lower end of the range. Economic assessments would need to be extended further into the supply chain to incorporate other transmission and distribution costs (inclusive of conversion and reconversion costs). This allows the cost-competitiveness of hydrogen to be determined for the targeted end-use application. Ultimately, it generates the requisite demand pull as well as price and quality signals for hydrogen and/or its derivatives.

For the MENA region, the Arab Petroleum Investments Corporation (APICORP) estimates that based on an average gas price of \$3–\$4/MMBtu, the LCOH for hydrogen produced by SMR coupled with CCUS would be \$1.5–\$2.5/kg. This assumes that the captured CO_2 would either be used as a feedstock in the petrochemicals or refining industries or permanently stored in geological formations. For renewable hydrogen via electrolysis, APICORP estimates that based on a levelized cost of electricity (LCOE) for renewable electricity of less than \$1.5/kWh, renewable hydrogen's LCOH would be \$2.5–\$3.5/kg. This assumes that MENA project developers can procure renewable electricity at prices similar to those obtained through competitively bid tariffs in awarded power purchase agreement concessions in Table 7.4. Such concessions are lower than the subsidized electricity tariffs offered to industrial users in most MENA countries, which range from a

TABLE 7.4 Independent solar photovoltaic projects' awarded bid tariffs in the Gulf Cooperation Council region

Country	*Solar PV Tariffs (US \$ cents/kWh)*	*Capacity (MW)*	*Date*
Saudi Arabia	1.04	600	April 2021
Abu Dhabi	1.35	2,000	April 2020
Qatar	1.57	800	January 2020
Saudi Arabia	1.61	300	April 2020
Dubai	1.69	900	December 2019
Saudi Arabia	1.99	400	January 2019
Saudi Arabia	2.34	300	February 2018

Source: The APICORP.

high 8.3 US¢/kWh for the UAE, a median 4.8 US¢/kWh for Saudi Arabia to a low 1.7 US¢/kWh for Kuwait (Strategy& 2020). Renewable electricity is the main cost driver of electrolysis.

Long-term prospects: IRENA has identified four MENA countries as candidates to become major hydrogen exporters: Oman, Morocco, Saudi Arabia, and the UAE. Of these, Morocco is transforming itself from an energy importer to an exporter, whereas the remaining three are pivoting from oil and gas to hydrogen. They are expected to compete with Australia, Canada, Chile, Namibia, Norway, and Russia. Notwithstanding renewable hydrogen production at an LCOH of less than $2/kg in 2050, IRENA has discounted MENA exporters' ability to mass-produce renewable hydrogen because of water scarcity (Figure 7.3).

Short-term prospects: S&P Global (2022a) provides dynamic assessments of the LCOH of several production pathways globally (Table 7.5). The July 2022 assessments indicate that GCC exporters would have a small cost advantage over Western Australia in reforming with CCS. However, they would be at a cost disadvantage in alkaline and polymer electrolyte membrane (PEM) electrolysis.

Local market competitiveness

New local hydrogen demand will be fueled by renewable and low-carbon ammonia and methanol production and local consumption in diverse transportation and energy applications. Hydrogen can reach a breakeven production cost for several applications in the MENA region by 2030.

The Hydrogen Council estimates that in MENA Countries, low-carbon hydrogen may already be cost competitive on a total cost of ownership basis with conventional alternatives in several applications. These include use of hydrogen in refining;

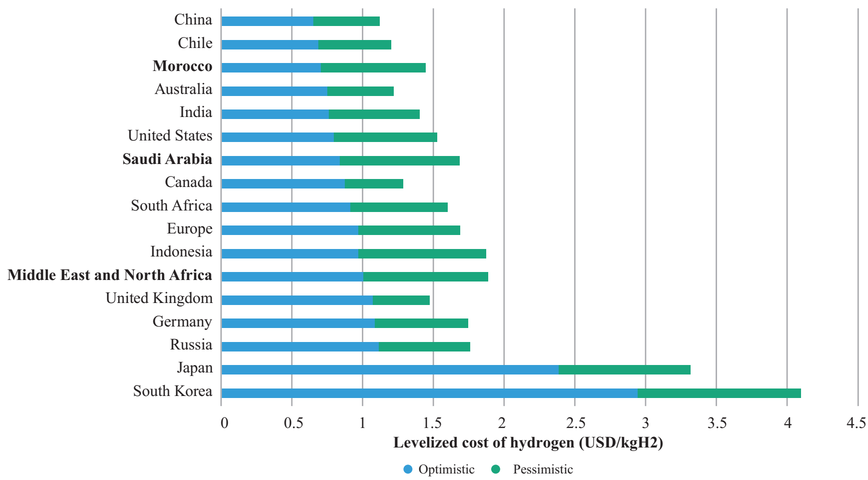

FIGURE 7.3 LCOH range in 2050.

TABLE 7.5 Current carbon-neutral hydrogen price assessments

Category	*Country*	*LCOH ($/kg) SMR+CCS**	*LCOH ($/kg) Alkaline Electrolysis*	*LCOH ($/kg) PEM Electrolysis*
MENA exporters	Oman	$4.07	$3.55	4.62
	Saudi Arabia	$4.03	$3.21	$4.23
	Qatar	$3.99	N/A	$3.52
	UAE	$4.13	$4.49	$5.7
Other exporters	Western Australia	$4.09	$2.75	3.85
	United States Gulf	$1.75 (ex. CCS)	$4.8	$6.07
Importers	Japan	$4.34 (ex. CCS)	$8.47	$10.58
	United Kingdom	$6.47	$11.47	$13.77
	The Netherlands	$6.38	$11.48	$13.76

Source: S&P Global (2022a). S&P Global Platts Hydrogen Price Wall, monthly average cost-of-production assessments include Capex and reflect a period of high natural gas prices (post-COVID-19 and Ukraine crises). S&P Global (2022c). The SP Global price assessments reflect the market value of hydrogen in which emissions have been, in order of priority: avoided where possible through the use of low emissions generation, removed through the use of carbon capture and storage, and offset through the use of carbon credits, renewable energy credits, or equivalent instruments.

ammonia in fertilizers and shipping; steel in the automotive industry (via direct iron reduction combined with steel scrap); and hydrogen in long-haul trucking (Hydrogen Council 2021b). The development of hydrogen clusters in export hubs, port areas, and industrial centers will increase the competitiveness of hydrogen applications substantially.

Short-term, renewable, and low-carbon hydrogen can decarbonize hard-to-abate energy-intensive industries such as refining, petrochemicals, fertilizers, steel and aluminum and long-haul transportation, and maritime shipping. Moreover, it can contribute to resilient and flexible electricity grids, especially those in the MENA region that experience peak load demand during the summer months. Hydrogen can facilitate integration into the intermittent renewable energy resource grid and compensate for the mechanical inertia lost due to the replacement of fossil fuel generation. However, it can also deliver fast-ramping peaking power.

Over the medium and long term, hydrogen can be a part of a portfolio of front-of-the-meter and behind-the-meter energy storage applications. In combination with battery storage, its role as a large-scale long-duration or seasonal energy storage medium will allow transmission system operators to optimally shave demand peaks and balance the grid. It will also avoid the curtailment of excess renewable energy capacity and provide demand-side responses, including frequency responses. This can enhance the capacity of energy storage systems to expand electricity trading on regional grid interconnections, which are underutilized in the MENA region. Finally, hydrogen can catalyze distributed energy applications in the residential, commercial, and industrial sectors (APICORP 2021).

MENA hydrogen roadmap

Figure 7.4 outlines a roadmap for MENA countries to carve out a competitive position in the energy transition using renewable and low-carbon hydrogen as catalysts. The roadmap comprises five pillars:

I Scale up commercially proven state-of-the-art low-carbon hydrogen production technologies;
II Create local demand applications for low-carbon hydrogen;
III Facilitate financing for first-of-a-kind hydrogen and CCUS projects;
IV Develop efficient and well-functioning markets for merchant hydrogen and derivatives to enable trading and match supplies with offtakes;
V Demonstrate key pre-competitive technologies with the potential to improve sustainability and reduce hydrogen production costs (Table 7.3).

Hydrogen state of play: early movers

The MENA region has already reacted to the hydrogen opportunity, with five countries emerging as early movers (K&L Gates 2021): Egypt, Morocco, Oman, Saudi Arabia, and the UAE. All five have begun renewable and low-carbon hydrogen and ammonia projects in partnership with international companies or are finalizing hydrogen

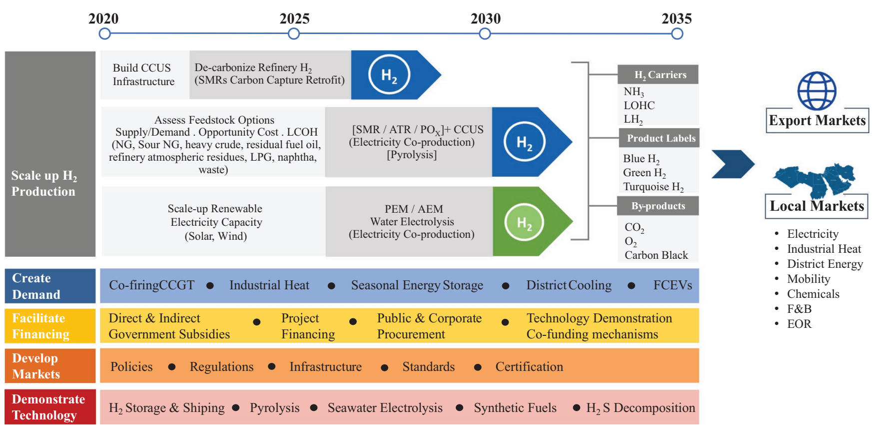

FIGURE 7.4 MENA hydrogen roadmap.

Source: Author.

roadmaps/strategies in collaboration with major demand centers. These early movers dominate the projects operating or under development in the MENA region.

The hydrogen strategies of these early movers are driven by different objectives, such as substituting imports and prolonging the life of hydrocarbon reserves. Moreover, they are expected to leverage their unique resource endowments, technical competencies, institutional capacities, and competitive positioning within the region and globally. This should expedite and enhance the effectiveness of their strategy implementation plans.

COP 27 and COP 28 being held in Egypt and the UAE, respectively, will drive them and other MENA countries to transform their announcements into concrete action. Thus far, the NDCs submitted by MENA countries have not set tangible quantitative targets despite substantial interest in hydrogen and CCUS (World Energy Council 2022). These landmark events are also galvanizing industry stakeholder support in demand centers and incentivizing them to deepen collaboration with the COP hosts through mutually beneficial projects and initiatives (Table 7.6).

TABLE 7.6 Features of selected MENA countries (early movers) pursuing clean hydrogen development

	Kingdom of Morocco
Competitive positioning	✓ Highly successful institutional framework for renewable energy project development ✓ Geographic proximity to end users in Europe ✓ Maghreb–Europe Gas Pipeline (11.5 bcm/y) connecting with the gas grids of Spain and Portugal could be repurposed for hydrogen or blending. ✓ Large local hydrogen and ammonia offtake opportunities (OCP Group, the world's largest phosphate producer, accounts for 10% of energy consumption.) ✓ Electricity interconnectors with Spain (2+1) and planned for Portugal, the United Kingdom, and East Africa
Strategy drivers	⇨ Become a leader in the production of renewable hydrogen via Power-to-X for domestic use and export, seeking to capture 4% of global production by 2030 ⇨ Reduce dependence on energy imports, accounting for 90% of its energy needs ⇨ Replace 2 mt/y of ammonia imports
Renewable energy targets	40% (2021); 52% by 2025 and 70% by 2040 (4.5 solar, 4.1 GW wind, and 1.3 GW hydro); 25 GW potential wind generation capacity (second in Africa, following South Africa)

(*Continued*)

TABLE 7.6 (Continued)

Project developers	OCP Group, Nareva, Port of Tanger Med, Institute for Research in Solar Energy and New Energies (IRESEN), Port of Hamburg, Fusion Fuel, Vitol, Consolidated Contractors Company (CCC), ACWA Power, Siemens Energy, Electricite de France (EDF), BASF, Vestas, Enel, John Cockerill
International collaboration	• Memorandum of understanding (MOU) with Germany • International agreement for the development of the **Green H_2 Cluster** in Morocco, a local hydrogen ecosystem driven by industrial innovation and research. Members include IRESEN, ACWA Power, Onhym, Nareva, Masen, OCP, Siemens Energy, EDF, Engie, BASF, Vestas, Enel, and John Cockerill.

Source: Author supported by Middle East Economic Survey (MEES 2021)

Republic of Egypt

Competitive positioning	✓ Emerging LNG hub for the Eastern Mediterranean (including potential extension of the EuroMed Gas Pipeline to Egypt) ✓ Suez Canal carrying approximately 12% of world seaborne trade ✓ Electricity interconnections with Jordan, Sudan, and Libya and soon with Saudi Arabia ✓ Plans for interconnectors with Cypress, Greece, and Iraq via Jordan ✓ Strong ammonia competencies (20 fertilizer plants in operation) ✓ Large local hydrogen and ammonia offtake opportunities ✓ Extensive industrial and infrastructure construction expertise ✓ Substantial cross-border investment from the UAE and Saudi Arabia in energy projects ✓ 11.62 GW pipeline of renewable hydrogen projects announced (as of May 2022)
Strategy drivers	⇨ Transform the Suez Canal Economic Zone into a global logistics hub connecting Europe, Africa, and Asia while leveraging the Arabian Gulf ⇨ Leverage the hub's desalination, sewage treatment, and ammonia bunkering facilities located in the Ain Sokhna region for hydrogen production and export ⇨ Leverage the abundant solar and wind resources to produce renewable hydrogen and derivatives for local consumption and exports ⇨ Maximize local content for hydrogen and related manufacturing industries ⇨ Replace unabated gray hydrogen consumption in the fertilizer, steel, refining, and petrochemical industries
Renewable energy targets	11% (2021); 20% of electricity generation by 2022 and 42% by 2035

(*Continued*)

TABLE 7.6 (Continued)

Project developers	OCI BV subsidiaries and affiliates, Egyptian Electricity Holding Company (EEHC), Egyptian Natural Gas Holding Company (EGAS), TAQA Arabia, Siemens, Eni, Dredging, Environmental and Marine Engineering NV (DEME) Concessions, Fluxys, Scatec, H2 Industries, ACWA Power, and AMEA Power
International collaboration	Egyptian state-owned enterprises signed MOUs with Siemens (Germany), DEME/Fluxys/Port of Antwerp (Belgium), Eni (Italy), Toyota Tsusho (Japan), Fertiglobe/ADNOC/Masdar/AMEA (UAE), Scatec (Norway), EDF (France), and ACWA (Saudi Arabia)

Source: Author supported by MEES 2021, Habib and Ouki (2021).

Sultanate of Oman

Competitive positioning	✓ Strategic global logistics position supported by established air, sea, and land connectively with regional and international markets ✓ Successful framework for the private development of renewable power projects ✓ World-class export infrastructure led by the ports of Duqm and Salalah ✓ First carbon-neutral liquefied natural gas cargo in MENA (June 2021)
Strategy drivers	⇨ Adopt the Oman Hydrogen Strategy targeting 40 GW of renewable energy for renewable hydrogen production by 2040 ⇨ Reduce vulnerability to the adverse impacts of climate change ⇨ Promote local offtake opportunities ⇨ Transform the Special Economic Zone at Duqm and Salalah Free Zone into major low-carbon industrial hubs ⇨ Repurpose existing and future hydrocarbon infrastructure
Key features	✓ Establishment of the Oman Hydrogen Center at the German University of Technology in Halban (GUTech) as a competency hub for research, technology, education, and industry applications ✓ Formation of the Oman Hydrogen Alliance (Hy-Fly) led by the Ministry of Energy and Minerals and including public and private organizations. These organizations comprise government bodies, oil and gas operators, educational/research institutes, and ports to support the production, transportation, and utilization of clean hydrogen for domestic use and export. They include the Authority for Public Services Regulation, Petroleum Development Oman, Energy Development Oman, OQ, Oman LNG, BP Oman, Oman Shell and Total Energies Oman, Sultan Qaboos University, GUTech, and the ports of Sohar and Duqm.

(*Continued*)

TABLE 7.6 (Continued)

Renewable energy targets	1% (2021). 10% of electricity generation by 2025 and 30% by 2030 Three Pillars Consulting is accredited by an international body (I-REC Standard Foundation) to issue renewable energy credits
Project developers	OQ, Ara Petroleum, Tatweer, InterContinental Energy, EnerTech, Dredging, Environmental and Marine Engineering NV (DEME) Concessions, ACWA Power, Air Products, Sumitomo, ACME Solar, and Uniper
International collaboration	Memorandum of understanding (MOU) to form Hydrogen Rise Oman (partnership between Hydrogen Rise (Germany) and Oman Educational Services). Several additional MOUs are outlined in the MENA Hydrogen Project Pipeline.

Source: Author supported by MEES 2021, Energy Oman (2021).

Kingdom of Saudi Arabia

Competitive positioning	✓ Architect/advocate of the G20-endorsed CCE framework ✓ Low-cost unconventional gas reserves that can be allocated to low-carbon hydrogen and ammonia production ✓ Home to Saudi Aramco, the world's largest energy company by market capitalization, and NEOM, a 100% renewable energy-powered region supported by a diverse industrial, technology, and services ecosystem ✓ Large hydrogen offtake opportunities in the well-established industrial hubs of Jubail, Yanbu, and Jazan ✓ 4 GW integrated gasification combined cycle power plant in Jazan producing unabated hydrogen as a by-product ✓ Considerable financial resources backed by some of the world's largest sovereign wealth funds ✓ Backbone of the Gulf Cooperation Council (GCC) Grid Interconnection Project
Strategy drivers	⇨ Achieve net-zero emissions target by 2060 (Saudi Aramco by 2050) ⇨ Implement the $101 billion renewable energy investment program ⇨ Capitalize on extensive energy ties with Asia ⇨ Leverage oil and gas reservoirs to enable large-scale cost-competitive carbon capture and storage (CCS) projects
Key features	• Earmarking a proportion of the massive unconventional (shale) gas reserves of Jafurah field for low-carbon hydrogen production instead of LNG
Renewable energy targets	1% (2021); 10% of electricity generation by 2025 and 50% by 2030; 27.3 GW of installed capacity by 2024 and 58.7 GW by 2030
CCS infrastructure	• Saudi Aramco is a member of the Oil and Gas Climate Initiative (OGCI), a CEO-led initiative focused on developing a net-zero strategy, reducing methane emissions and carbon intensities and scaling up CCS • See the list of CCS projects in the section titled **Institutional capacity for hydrogen project development and financing**

(*Continued*)

TABLE 7.6 (Continued)

Project developers	Saudi Aramco, Saudi Basic Industries Corporation (SABIC), NEOM, Royal Commission of Jubail and Yanbu, ACWA Power, Air Products, Hyundai, and Korea Shipbuilding and Offshore Engineering Company (KSOEC)
International collaboration	• Government-to-government agreements with Germany and business-to-business agreements with Japan and South Korea • Member of Mission Innovation, including its clean hydrogen mission • Saudi Aramco is a member of the Hydrogen Council and the Oil & Gas Climate Initiative (OGCI).

Source: Author supported by MEES (2021).

United Arab Emirates

Competitive positioning	✓ First MENA country to commit to achieving net-zero by 2050 ✓ Substantial sour gas reserves that can be allocated to low-carbon hydrogen and ammonia production ✓ Commissioned first renewable hydrogen project (Expo 2020) and hydrogen refueling station in the MENA region (2017) ✓ Fujairah (world's third-largest bunkering hub) candidate for ammonia bunkering ✓ Masdar, a renewable energy developer and investor powerhouse ✓ 5 GW of nuclear generation capacity ✓ Al Dhafra solar plant holds the record for the lowest levelized cost of electricity (LCOE). ✓ Substantial sour gas reserves that can be allocated to low-carbon hydrogen and ammonia production ✓ Considerable financial resources backed by some of the world's largest sovereign wealth funds
Strategy drivers	⇨ Achieve net-zero emissions target by 2050 ⇨ Implement the Hydrogen Leadership Roadmap, which calls for capturing a 25% market share by 2030 ⇨ Seek early-mover advantage as a low-carbon and renewable hydrogen producer ⇨ Develop over 50 GW of renewable capacity by 2030 ⇨ Decarbonize oil production, refining, and LNG operations ⇨ Develop clean energy hubs internationally ⇨ Evaluate synthesis fuel production with an initial focus on e-kerosene ⇨ Reduce the carbon footprint of hydrogen and ammonia production ⇨ Develop the Ta'ziz Derivatives Park at Ruwais as a world-scale chemical production hub and industrial ecosystem ⇨ Develop private sector capacity

(*Continued*)

TABLE 7.6 (Continued)

Key features	• Consolidate and pool resources within the public sector through the formation by Mubadala, Abu Dhabi National Oil Company (ADNOC), Abu Dhabi Developmental Holding Company (ADQ), and Abu Dhabi National Energy Company (TAQA) of the Abu Dhabi Hydrogen Alliance and adding TAQA and ADNOC as shareholders in Masdar, formerly a subsidiary of Mubadala • ADNOC's purchase of nuclear and renewable electricity from Emirates Water and Electricity Company to power its upstream and downstream facilities as evidenced by green certificates issued by the Department of Energy accredited by the I-REC Standard Foundation • Formulation of a technical regulation for hydrogen fuel cell vehicles by Emirates Authority for Standardization and Metrology
Renewable energy targets	Dubai: 25% of electricity generation by 2030 and 75% by 2050 UAE Federal: 5% (2021); 44% of electricity generation by 2050, including nuclear power The Abu Dhabi Department of Energy and the Dubai Electricity and Water Authority (DEWA) are accredited by an international body (I-REC Standard Foundation) to issue renewable energy credits.
CCS infrastructure	There are plans to increase CCS capacity to 4.3 mt/y by 2030. Al Reyadah CCUS facility was commissioned in 2016 and recovers 800,000 t/y of carbon dioxide (CO_2). See the section titled **The Arabian Lights project: Toward a regional role for Saudi Arabia.**
Project developers	ADNOC, TAQA, Mubadala, Masdar, ADQ, DEWA, Abu Dhabi Ports, Fertiglobe, Inpex, JERA, Siemens, Marubeni, BP, Engie, Itochu, Mitsui & Co., and GS Energy
International collaboration	• There are government-to-government agreements with Germany, Austria, the Netherlands, Malaysia, Japan, and South Korea. • UAE is a member of the International Partnership for Hydrogen and Fuel Cells in the Economy. • Mubadala and ADNOC are members of the Hydrogen Council.

Source: Author supported by MEES (2021).

Hydrogen state of play: project pipeline

A total of 47 renewable and low-carbon hydrogen projects at an estimated cost of \$55 billion have been announced in the MENA region. Most are renewable hydrogen and ammonia projects (75%) and have been announced by the early movers: Morocco (six), Egypt (nine), Oman (seven), Saudi Arabia (four), and the UAE (15); Clean Energy Business Council 2022).

Some of these projects are under development, with final investment decisions expected toward the end of 2022 or in early 2023. The projects have been developed by industry consortia comprising local and international companies. Lead developers from the MENA region comprise national oil companies (NOCs), sovereign wealth funds (SWFs), state-owned energy enterprises, independent power developers, and fertilizer companies. Their international consortium partners include a wide range of companies from Belgium, France, Germany, India, Italy, Japan, the Netherlands, Norway, South Korea, the United Kingdom, and the United States. These companies include original equipment manufacturers, Japanese trading companies, industrial gas companies, major energy companies, energy traders, utilities and steel manufacturers (Tables 7.6 and 7.7).

TABLE 7.7 Middle East and North Africa's renewable hydrogen project pipeline

Country	*Project*	*Cost*	*Hydrogen*	*Ammonia*	*Electricity*	*Startup*	*Developers*
Operating							
UAE	Dubai Expo	$14 million	180 t/y	n/a	1.25 MW	2020	Pilot by DEWA and Siemens Energy
In development							
Egypt	Ain Sokhna, (Gulf of Suez)	n/a	16,000 t/y	90,000 t/y	185 MW	2022	Fertiglobe/Orascom/Scatec
	Waste-to-Hydrogen (Port Said)	$3 billion	300,000 t/y		4 mt/y plastic and organic waste	2026	SCZone /H2 Industries
Saudi Arabia	NEOM Green Hydrogen Company (NEOM City)	$5 billion	237,000 t/y	1.2 Mt/y	4 GW	2026	ACWA Power/Air Products /NEOM
UAE	Helios (Kizad)	$1 billion	40,000 t/y	200,000 t/y	800 MW	n/a	NGHC/ThyssenKrupp
Oman	Hyport (Duqm)	n/a	20,000 t/y		250–500 MW	2026	OQ/DEME/Uniper
UAE	Waste-to-Hydrogen (Sharjah)	$180 million	6,570 t/y to refueling stations		Plastic and organic waste	2023	Bee'ah/Chinock Sciences
Country	*Project*	*Cost*	*Hydrogen*	*Ammonia*	*Electricity*	*Startup*	*Developers*
Memorandum of understanding (MOU)/strategic framework agreements/feasibility studies							
Morocco	HEVO Project	$850 million	31,000 t/y	183,000 t/y	400 MW	2026	Fusion Fuel/Vitol/CCC
Oman	Green Mega Fuels Project (Al Wasta)	$30 billion	1.75 mt/y	9.9 mt/y	25 GW	2023	OQ/InterContinental Energy/EnerTech
	MOU for the development of an 800,000-t/y green ammonia project in the special economic zone at SEZAD (Duqm) at a cost of $2.5 billion						ACME Solar Holdings/Tatweer
	Joint development agreement for a 400-MW electrolysis and 360,000-t/y green ammonia project						OQ/Marubeni/Linde/Dutco Group
	MOU for a feasibility study for the development of a 1-mtpa renewable ammonia project in Dhofar						OQ/ACWA Power/Air Products
UAE	Joint venture for the development of up to 30 GW of renewable energy capacity and a renewable hydrogen market						ADNOC/TAQA
	Agreement for the development of a renewable hydrogen and synthesis fuels pilot project to fuel buses/heavy transportation and produce aviation fuels (e-kerosene)						Masdar, Mubadala, ADNOC, Siemens, Marubeni, Etihad, Lufthansa, DoE, Khalifa University

(*Continued*)

TABLE 7.7 (Continued)

Country	*Project*	*Cost*	*Hydrogen*	*Ammonia*	*Electricity*	*Startup*	*Developers*
	Strategic framework agreement for the development of a clean hydrogen hub based on 2 GW of renewable energy electricity capacity						BP/ADNOC/Masdar
	MOU to explore co-development of a green hydrogen hub by 2030 at an estimated cost of $5.0 billion based on 2 GW of renewable energy electricity capacity						Masdar/Engie
	MOU for the development of hydrogen-derived synthetic fuels						Mubadala/Siemens
	MOU for the development of a 2 GW green ammonia storage, export, and bunker fuel project to be based in Kizad						TAQA/Abu Dhabi Ports
	MOU for the evaluation of hydrogen development and investment opportunities						Mubadala/Snam
	Strategic framework agreement for hydrogen, CCUS, EOR, and unconventional gas development						ADNOC/Petronas
	Agreement for the development of a decarbonization roadmap for Abu Dhabi's downstream operations						ADNOC/GE Gas Power
	Partnership to co-develop the HyGreen Teeside green hydrogen project (United Kingdom) to produce 60 MWe of hydrogen by 2025, increasing to 500 MWe by 2030						Masdar/BP
	Feasibility study to explore the production of synfuels for aviation using municipal waste as a feedstock						ADNOC/Masdar/Tadweer/Etihad Airways/BP
Egypt	MOU to co-develop a 100–200-MW green hydrogen pilot project for export						EEHC/Siemens
	MOU to assess the technical and commercial feasibility of green and blue hydrogen production						Eni/EEHC/EGAS
	Feasibility study for a green hydrogen project for export to Europe						DEME/Fluxys
	Cooperation agreement to develop up to 4 GW electrolysis capacity to produce 2.3 mt/y of green ammonia and 100,000 t/y of e-methanol for bunkering in the Suez Canal						EMERA/SFE/SCZONE/Masdar/Hassan Allam
	MOU for a 240,000-t/y project to produce green ammonia and hydrogen in Ain Sokhna						SCZONE/SFE/EETS/AMEA Power
	MOU for a 350,000-t/y project at a cost of $3 billion in Ain Sokhna to produce green ammonia for bunkering with startup scheduled for 2026						SCZONE/SFE/EDF/Zero Waste
Mauritania	Prefeasibility study to assess the technical and commercial viability of up to 10 GW green hydrogen export project (Project Nour)						Chariot/Ministry of Petroleum, Mines & Energy
Algeria	Prefeasibility study to assess the technical and commercial viability of a pilot project for green hydrogen production						Eni/Sonatrach
Morocco	MOU to develop an industrial-scale green hydrogen production plant						Ministry of Energy and Minerals/BMZ
	MOU to promote hydrogen technologies (including the electrocatalytical synthesis of ammonia, biotechnological phosphorous modification) and develop a Power-to-X ecosystem in IRESEN's Green Energy Park, Ben Guerir, Morocco						IRESEN/OCP Group/Fraunhofer IGB
	Letter of intent for the export of renewable hydrogen to Germany encompassing port cybersecurity and digitalization procedures						Port of Tanger Med/Port of Hamburg
	Repurposing the Sahara Wind Initiative to develop regional green hydrogen platform in Maghreb countries and Mauritania						NATO/IPHE/Sahara Wind

Source: Author supported by MEES 2021; S&P Global (2022a); IEA; World Hydrogen Leaders Platform

(*Continued*)

TABLE 7.7 (Continued)

Legend:
ADQ: Abu Dhabi Developmental Holding Company.
BMZ: The German Federal Ministry of Economic Cooperation.
CCC: Consolidated Contractors Company.
DEME: Dredging, Environmental and Marine Engineering NV.
DEWA: Dubai Electricity and Water Authority.
DoE: Abu Dhabi Department of Energy.
EEHC: Egyptian Electricity Holding Company.
EETC: Egyptian Electricity Transmission Company.
EGAS: Egyptian Natural Gas Holding Company.
EMERA: Egyptian Ministry of Electricity and Renewable Energy.
IEEJ: Institute of Energy Economics Japan.
IPHE: International Partnership for Hydrogen and Fuel Cells in the Economy.
IRESEN: Moroccan Research Institute for Solar and New Energies (IRESEN).
JOGMEC: Japan Oil, Gas and Metals National Corporation.
KIZAD: Khalifa Industrial Zone Abu Dhabi.
KSOEC: Korea Shipbuilding and Offshore Engineering Company.
MASEN: Moroccan Agency for Sustainable Development.
METI: Japan Ministry of Economy, Trade and Industry.
NATO: The North Atlantic Treaty Organization.
NREA: Egyptian New & Renewable Energy Authority.
SCZONE: Suez Canal Economic Zone.
SEZAD: Oman Special Economic Zone at Duqm.
SFE: Sovereign Fund of Egypt.
Tadweer: Abu Dhabi Waste Management Center.
TAQA: Abu Dhabi National Energy Company.
Tatweer: Company for Development of Special Economic Zone at Duqm (Oman).

Capacity building for hydrogen project development and financing

Compared to renewable hydrogen, low-carbon fossil hydrogen projects are likely to have higher capital requirements, larger infrastructure demands (to access CCUS capacity), and higher engineering sophistication. Therefore, they are better suited for energy majors and NOCs, which have access to the required capital, infrastructure and technical resources, and a proven track record as gray hydrogen producers. However, renewable hydrogen projects are more suited to private developer consortia, where numerous project risks are allocated to members of the consortium deemed acceptable to debt lenders. These projects are based on securing access to independent power projects that generate electricity from renewable sources such as solar and wind energy.

In theory, the MENA region possesses the necessary capacity to develop low-carbon fossil and derivative projects and houses, some of the world's leading NOCs. **Saudi Aramco** (Saudi Arabia), the world's largest publicly listed energy company, Abu Dhabi NOC **(ADNOC)** (UAE), and **OQ** (Oman) have ambitious hydrogen and CCUS strategies. Some have embarked on the development of large-scale, first-of-a-kind hydrogen and ammonia projects. **Sonatrach** (Algeria), Africa's the largest oil and gas company, is expected to capitalize on its early lessons from the In Salah CCS project, the first in the MENA region.

In addition to NOCs, the MENA region is home to large state-owned enterprises that have become national champions and committed to low-carbon hydrogen and its derivatives. The Abu Dhabi National Energy Company (**TAQA**) (UAE) is a regionally integrated electric power and water utility company listed on the Abu Dhabi Securities Exchange. It has $50.8 billion in assets and 22.6 GW of power generation capacity (gross) under management (TAQA 2022).

The **OCP Group** (Morocco), a vertically integrated fertilizer company, is the world's largest producer and exporter of phosphate rock and phosphoric acid and second largest producer of phosphate-based fertilizers. It had annual production capacities of 46.6 mt, 7.7 mt, and 12.0 mt of phosphate rock, phosphoric acid, and phosphate-based fertilizers in 2020, respectively. To replace the 2 mt of ammonia imported annually, OCP has developed a strategy to synthesize green hydrogen and ammonia feedstocks for use in fertilizer production.

The MENA region is home to 14 of the world's 25 largest SWFs, with combined assets of $3.5 trillion in 2021 (Sovereign Wealth Fund Institute 2021). Two wealth funds, namely, **the Public Investment Fund** (Saudi Arabia) and **Mumtalakat** (Bahrain), have played a role in capitalizing two of the private sector champions namely: ACWA Power and Gulf Cryo. The **Mubadala Investment Company** (UAE) has already initiated several hydrogen-related projects and initiatives. Along with industrial investment companies such as **Dussur** (Saudi Arabia), these SWFs will expand their role as private equity investors and act as venture capitalists to seed local hydrogen and CCUS ecosystems.

However, the prospects are much less favorable for the private sector's capacity for energy project development. With a few exceptions, state-owned enterprises in the MENA region have crowded out the private sector. They have confined their role to the supply and provision of contracted services and equipment, often in partnership with international contractors and original equipment manufacturers. Going forward, MENA governments should assist the private sector, particularly SMEs, in developing renewable hydrogen production projects and spearheading the development of domestic hydrogen ecosystems.

It is entrepreneurial companies and SMEs, and not large electric utilities, which are pioneering innovation in the electricity sector. The same is likely to hold true for hydrogen. A recent analysis by Hydrogen Europe determined that of the 280 companies actively developing hydrogen technologies in Europe, 170 were SMEs (Hydrogen Europe 2020). Therefore, MENA governments will need to reduce entry barriers, create a level playing field, and seed supporting ecosystem development (with policies and financial incentives). This will allow private sector companies, particularly SMEs, to develop or acquire the necessary capacity to

- Develop hydrogen and hydrogen-related projects;
- Deploy, operate, maintain, adapt, improve, and reproduce imported hydrogen technologies;
- Invent new technologies and commercial solutions tailored to local consumer requirements.

Notwithstanding capacity and regulatory challenges, the MENA region has produced a number of private sector champions (Table 7.8). **ACWA Power** (Saudi Arabia) is a global independent power producer and owns over 22 GW of power generation capacity, worth more than $32 billion, across 11 countries. Other independent power producers have started charting their own courses, such as **Nareva** (Morocco), **Infinity** (Egypt), and **AMEA Power** (UAE). **OCI** (Egypt/the Netherlands) is one of the world's leading producers of ammonia and methanol. Its joint venture with ADNOC, Fertiglobe, has recently completed an initial public offering on the Abu Dhabi Securities Exchange, which was oversubscribed by 22 times. **Gulf Cryo** (Kuwait) is a leading manufacturer of industrial, medical, food-grade, and specialty gases in the Middle East.

The MENA region's project financing capacity will also need to be increased substantially, with most of the burden on the two regional development organizations. The **Gulf Investment Corporation** is a regional development bank established in Kuwait by the six GCC member states with $3.27 billion in assets (Gulf Investment

TABLE 7.8 Middle East and North Africa's low-carbon fossil hydrogen project pipeline

Country	*Project*	*Cost*	*Hydrogen*	*Ammonia*	*CCS*	*Startup*	*Developers*
Operating pilots							
Saudi Arabia	Demonstrate the production and shipment (September 2020) of the world's first blue ammonia cargo (to Japan) The carbon dioxide (CO_2) captured from hydrogen production (which in turn is used as a feedstock for Haber–Bosch ammonia synthesis) is used to produce methanol at Saudi Basic Industries Corporation's (SABIC) Ibn-Sina plant in Jubail Industrial City. It is also utilized for enhanced oil recovery (EOR) at the Uthmaniyah oilfield.						Saudi Aramco/SABIC/IEEJ/METI
UAE	Sold blue ammonia cargo to Japan (August 2021)						ADNOC/Itochu Corporation
In development							
UAE	TA'ZIZ Industrial Hub (Ruwais)	n/a	200,000 t/y	1.0 mt/y	Al Reyadah CCS Project	2025	ADNOC/Fertiglobe/ADQ/Mitsui & Co./GS Energy
Saudi Arabia	Agreement for the development of a blue hydrogen project in South Korea based on imported LPG feedstock from Saudi Arabia Blue hydrogen to be used in liquefied natural gas boilers and sold as fuel for fuel cell vehicles in South Korea CO_2 generated during hydrogen production to be captured, stored, and shipped back to Saudi Arabia for use in EOR Dual-use liquefied petroleum gas (LPG)-CO_2 ammonia-fueled ships will also be developed.						Saudi Aramco/Hyundai/Hyundai Oilbank/KSOEC
	Production of 11 mtpa of blue ammonia by 2030						Saudi Aramco

(*Continued*)

TABLE 7.8 (Continued)

Country	*Project*	*Cost*	*Hydrogen*	*Ammonia*	*CCS*	*Startup*	*Developers*
Qatar	Production of 1.2 mtpa of blue ammonia in Masaieed Industrial City with planned start of production scheduled for Q1 2026						Qafco/Qatar Energy Renewable Solutions
Memorandum of understanding (MOU)/ strategic framework agreements (SFA)/feasibility studies							
UAE	Feasibility study to explore the commercial potential of blue ammonia production in the UAE						ADNOC/INPEX/ JERA/JOGMEC
	Partnership to co-develop the H2Teeside blue hydrogen project (United Kingdom), taking a 25% ownership in the pre-FEED stage						ADNOC/BP
	Project plans to develop 1 GWe of hydrogen production by 2030						
Saudi Arabia	The Ministry of Energy has declared that a large proportion of the natural gas from the estimated $110 billion development of the Jafurah Gas Field will be earmarked for blue hydrogen production instead of LNG. The field is estimated to have 200 trillion cubic feet of reserves and could begin production in 2024.						Saudi Aramco
Oman	MOU to develop 300–400 t/y of blue hydrogen using flared gas generated during oil and gas production as feedstock; a 20-MW solar plant to power the hydrogen plant						Ara Petroleum/ Sumitomo Corporation
	Hydrogen to be used as fuel for fuel cell vehicles at oil and gas production sites						

Sources: Author supported by MEES (2021); S&P Global (2022a); IEA (2021a); World Hydrogen Leaders Platform (2022); author.

Legend:
ADQ: Abu Dhabi Developmental Holding Company.
BMZ: The German Federal Ministry of Economic Cooperation.
CCC: Consolidated Contractors Company.
DEWA: Dubai Electricity and Water Authority.
DoE: Abu Dhabi Department of Energy.
EEHC: Egyptian Electricity Holding Company.
EETC: Egyptian Electricity Transmission Company.
EGAS: Egyptian Natural Gas Holding Company.
EMERA: Egyptian Ministry of Electricity and Renewable Energy.
IEEJ: Institute of Energy Economics Japan.
IPHE: International Partnership for Hydrogen and Fuel Cells in the Economy.
IRESEN: Moroccan Research Institute for Solar and New Energies (IRESEN).
JOGMEC: Japan Oil, Gas and Metals National Corporation.
KIZAD: Khalifa Industrial Zone Abu Dhabi.
KSOEC: Korea Shipbuilding and Offshore Engineering Company.
MASEN: Moroccan Agency for Sustainable Development.
METI: Japan Ministry of Economy, Trade and Industry.
NATO: The North Atlantic Treaty Organization.
NREA: Egyptian New & Renewable Energy Authority.
Qafco: Qatar Fertilizer Company.
SCZONE: Suez Canal Economic Zone.
SEZAD: Oman Special Economic Zone at Duqm.
SFE: Sovereign Fund of Egypt.
Tadweer: Abu Dhabi Waste Management Center.
TAQA: Abu Dhabi National Energy Company.
Tatweer: Company for Development of Special Economic Zone at Duqm (Oman).

TABLE 7.9 Private sector champions in Middle East and North Africa

	ACWA Power	*OCI BV*	*Gulf Cryo*
Industry segment	Independent power producer	Fertilizer producer	Industrial gases company
Annual revenues	$1.4 billion (2021)	$6.3 billion (2021)	$150 million (2021)
Market capitalization	$27.9 billion (April 2022)	$8.26 billion (May 2022)	N/A
Role in energy transition	Scale up renewable electricity capacity globally and open the market to followers who accelerate the commercial deployment of technologies.	Co-develop renewable and low-carbon hydrogen and ammonia projects by leveraging ammonia's position in three ways.	Co-develop renewable and low-carbon hydrogen and ammonia projects.
	Well positioned to extend a proven track record in renewable electricity and water desalination project development to electrolytic hydrogen and derivatives, including ammonia.	The first is as the world's second-most widely produced commodity (183 mt/y in 2020), which is expected to grow to over 600 mt/y by 2050. The second is as an efficient hydrogen carrier. The third is as a fuel used directly in shipping and electricity generation.	Provide outsourced carbon capture, storage, and utilization services by leveraging competencies in the transportation, storage, and distribution of industrial gases across the energy supply chain. These include gray hydrogen production, air separation, liquid-to-gas conversion, high pressure compressed gases handling, and associated safety practices.
Formation	Established in 2008 in Saudi Arabia Headquartered in Riyadh, Saudi Arabia with regional offices in Dubai, Istanbul, Cairo, Rabat, Johannesburg, Hanoi, and Beijing	Established in 1999 in Egypt as Orascom Construction Industries (spun off in 2015 on Nasdaq Dubai) and redomiciled in Amsterdam as OCI BV in 2019 Headquartered in Amsterdam, the Netherlands.	Established in 1953 in Kuwait Headquartered in Kuwait and Dubai

(*Continued*)

TABLE 7.9 (Continued)

	ACWA Power	*OCI BV*	*Gulf Cryo*
Operations	64 projects in operation, under construction or in advanced development in 12 countries (2021)	One of the world's largest ammonia and CH_3OH producers worldwide and the largest seaborne merchant exporter of ammonia globally	Largest merchant air separation unit and dry ice manufacturing capacity in the region. Operations in 10 Middle Eastern countries, serving the upstream oil and gas, refining, petrochemicals, metals and steel, food and beverage, glass, mining, construction, electronics, and healthcare industries
	42.7 GW (gross) of installed power generation capacity and 6.4 billion m^3/d (gross) water desalination capacity	The company has 3,600 employees.	The company has 1,250 employees.
	The company has 3,500 employees.	Fertiglobe is a 60/40 owned joint venture with Abu Dhabi National Oil Company (ADNOC) covering operations in the MENA region.	
Business model	Fully contracted long-term offtake agreements with electricity and water price and volume protections against demand, currency, and regulatory risks	Chemical commodity producer and trader	Medium and long-term take-or-pay supply contracts with creditworthy industrial companies
Capital structure	Publicly listed on Tadawul, Saudi Arabia (2021)	Publicly listed on Euronext, the Netherlands (2013)	Privately owned
		Fertiglobe is publicly listed on the Abu Dhabi Securities Exchange, UAE.	Established in 1953 in Kuwait and headquartered in Kuwait and Dubai
Role of government	Saudi's Public Investment Fund has 44.16% ownership. International Finance Corporation (IFC) was an investor (2014–2020).	ADNOC (UAE) is a 40% shareholder of the Fertiglobe subsidiary.	Bahrain's Mumtalakat was an early investor.

(*Continued*)

TABLE 7.9 (Continued)

	ACWA Power	*OCI BV*	*Gulf Cryo*
Hydrogen/ CCUS project pipeline	Co-developer, NEOM green ammonia project, Saudi Arabia (Table 7.4)	Co-developer, via Fertiglobe, Ain Sokhna, Gulf of Suez, Egypt (Table 7.4)	Carbon dioxide (CO_2) recovery plant capacity expected to reach 250,000 t/y by the end of 2022, largest in the Middle East
	Founding member, Green Hydrogen Catapult initiative, which aims to develop up to 25 GW of renewable hydrogen capacity globally	Carbon capture and storage projects in the Netherlands, the United States and MENA	Producer of grid-based electrolytic hydrogen with plans to expand to renewable hydrogen
		Partnerships with ExxonMobil/ Essar (Biofuels); RWE (waste-to-hydrogen); Nouryon/RWE (synthetic CH_3OH); Eastern Pacific Shipping, /Hartmann Group, /Man Energy Solutions (low-carbon ammonia and CH_3OH)	Expansion into carbon capture and storage-enhanced oil recovery and energized CO_2 fracking for natural gas fields

Source: ACWA Power (2021); OCI BV (2021); Fertiglobe (2021); Gulf Cryo (2021).

Corporation 2021). **APICORP** is a multilateral development bank established in Al Khobar (Saudi Arabia) by 10 Organization of Arab Petroleum Exporting Countries member states with $7.89 billion of assets in 2021. APICORP is expected to play a key role in financing hydrogen, ammonia, and CCS projects in the MENA region. It recently announced a framework to govern the issuance of green bonds. This would enable it to expand the share of green financing within its lending and investment portfolios and invest up to $1 billion in green energy projects and companies (APICORP News 2021). Owing to its experienced human resources and progressive vision, APICORP is expected to play a critical role in financing hydrogen and CCS projects.

The MENA region scores poorly in terms of innovation. The UAE ranks within the top 50 countries in the Global Innovation Index (2021) rankings. Research institutions in the MENA region can thus become key stakeholders and make tangible contributions to demonstration and pilot projects aimed at commercializing hydrogen and CCUS technologies. Technologies with the potential to improve the competitiveness of hydrogen projects in the MENA region are outlined in Annex 1 MENA hydrogen roadmap. Several research institutions have taken the lead in this regard. As members of the CCE National Program, King Abdullah Petroleum Studies and Research Center (**KAPSARC**) and **King Abdullah University of Science and Technology** (KAUST) helped develop the CCE framework (CCE National Program 2021). In collaboration with the IEA, the Global CCS Institute, Organisation for Economic Co-operation and Development (OECD), IRENA, Nuclear Energy Agency, and KAPSARC (2020) published the CCE Guide, which has been disseminated globally.

NOCs can make a considerable contribution. **Saudi Aramco** has research and technology centers and research programs with leading local universities such as KAUST. In addition, it operates such centers in China, France, the Netherlands, Russia, Scotland, Saudi Arabia, and the United States (three centers). It is also collaborating with industrial gas companies (e.g., Air Products) to develop refueling infrastructure for FCEVs. The first refueling station was commissioned in the Dhahran Techno Valley Science Park in June 2021. **Saudi Aramco** is partnering with car manufacturers (Toyota and Hyundai) on fuel cells and the advancement of the hydrogen economy. In addition, it has partnered with several Japanese companies to evaluate the feasibility of using LPG as a hydrogen carrier and the subsequent transportation of CO_2. Saudi Aramco has advanced and showcased its proprietary mobile carbon capture technology as an example for reducing the carbon footprint of transportation. Other institutions within Saudi Arabia include **King Abdulaziz City for Science and Technology**, **King Fahad University of Petroleum and Minerals,** and the **Center of Research Excellence in Renewable Energy**.

The **ADNOC Research and Innovation Center**, managed jointly by **ADNOC** and **Khalifa University** in the UAE, is poised to play a critical role. Khalifa University is a part of the e-kerosene pilot project. It is also collaborating with Air Liquide and Al-Futtaim Motors to develop hydrogen refueling stations and lease FCEVs to government institutions. **Masdar** is involved in the e-kerosene pilot project. Moreover, it is collaborating with BP and ADNOC to develop low-carbon hydrogen and CCUS hubs in the UAE and the United Kingdom and decarbonized air corridors between the two (BP 2021). Although not focused on energy transition technologies, **the Kuwait Petroleum Corporation** has a research and technology center in Rotterdam, the Netherlands. This center is well positioned to develop hydrogen-related technologies in collaboration with industry partners.

Sultan Qaboos University and German University of Technology **(GUTech)** are members of the Oman Hydrogen Alliance (Hy-Fly). **Muscat University** is collaborating with Cranfield University in the United Kingdom to reduce the carbon footprint of LNG production. The latter was made possible by **Ejaad**, a platform organization bringing institutions from the government, industry, and academia together to collaborate in research and development (R&D). Hosted by GUTech, the **Oman Hydrogen Center** was created to build competencies within Oman through collaboration with national and international research partners. The Center's R&D activities include hydrogen use cases and applications and modeling and optimizing the hydrogen supply chain in Oman. The **Moroccan Research Institute for Solar and New Energies** has galvanized support from industry players for the **Green H_2 Cluster**, which is driven by industrial innovation and research.

A key requisite for the development of a well-functioning, transparent, and efficient hydrogen market is a globally accepted certification scheme. Such schemes track the environmental and sustainability attributes of the hydrogen and CCUS supply chains. While several national and regional schemes are being developed worldwide, none have yet become operational (IRENA 2022d). In the interim, **TÜV Rheinland**, a German independent testing, inspection, and certification agency, is conceptually certifying the GHG emissions associated with two hydrogen and ammonia production projects. These are the **ACME Group**'s green ammonia project (TÜV Rheinland Insights 2022) and **Aramco** and Saudi Basic Industries Corporation's **(SABIC**'s) integrated hydrogen and ammonia project, inclusive of CCU (Table 7.4; SABIC 2022).

As hydrogen is not a primary energy source and both renewable and low-carbon hydrogen production require significant renewable electricity inputs, tracking electricity and hydrogen attributes should be integrated. For over a decade, energy attribute certificates (EACs) have been traded and sold separately from the electricity to which they are attributable. Several strides have been made in the MENA region.

The **Dubai Electricity and Water Authority** (DEWA) and **Abu Dhabi Department of Energy** are the leading issuers of EACs in the form of renewable energy credits (I-RECs). These are accredited by the I-REC Standard Foundation, a non-profit standard-setting body. I-RECs validate power producers and end users' claims that the energy and/or product output and the electricity consumed, respectively, are renewable. Several renewable solar and wind projects in MENA have begun issuing I-RECs. Table 7.10 lists the project registrants.

Three notable examples are worth highlighting. In a landmark development in 2021, **Emirates Global Aluminum** procured 560,000 MWh of solar electricity

TABLE 7.10 Renewable energy project registrations for electricity energy attribute certificates

Country	*Project*	*Technology*	*Capacity*	*Registration*
 Egypt	Benban	Solar photovoltaic (PV)	378 MW	January 2020
	Ras Ghareb Wind Energy	Wind onshore	262 MW	June 2019
	Solar Park (Benban 2)	Solar PV	50 MW	January 2020
 Jordan	Al Mafraq Solar Park	Solar PV	50 MW	April 2018
	Al Ambaratouria Solar Park	Solar PV	67 MW	June 2019
	FRV Solar Holdings	Solar PV	67 MW	June 2020
 Morocco	Noor 1 Solar	Solar CSP	160 MW	January 2018
	Khalladi Wind Farm	Wind onshore	120 MW	January 2018
 Oman	Amin Ground Mounted Solar PV Plant	PV Solar	105 MW	May 2022
	PV Barka Solar Plant (Al Madina Logistics Services Company, AMLS)	PV Solar	1.65 MW	May 2022
 Saudi Arabia	Sakaka PV	Solar PV	300 MW	January 2021
 UAE	Barakah Nuclear Plant	Nuclear	1,390 MW	August 2020
	Sweihan PV Plant		935 MW	August 2020
	Mohamed bin Rashid Solar Park Phase 3	PV Solar	800 MW	January 2019
	Mohamed bin Rashid Solar Park Phase 2	PV Solar	200 MW	March 2017
	Mohamed bin Rashid Solar Park Phase 1	PV Solar	13 MW	January 2017
	CMX-1 Solar	Solar PV Aggregated	4 MW	January 2020

Source: Evident Registry (2022).

from the Mohammed bin Rashid Al Maktoum Solar Park. This supported the claim that the 40,000 mt of aluminum intended for one of its clients, Germany's BMW, were green, or labeled CelestiAL (Emirates Global Aluminum 2021). In another development, the Abu Dhabi Department of Energy issued clean energy certificates based on the same attribute tracking standard as that for I-RECs. This validated its claim that the energy procured by **ADNOC** for its internal electricity requirements is 100% generated by low-carbon nuclear power (Abu Dhabi Department of Energy 2021). In 2018, the Khalladi Wind Farm in Morocco, owned and operated by **ACWA Power**, issued I-RECs for each MWh generated (ACWA Power 2018). This initiative enabled industrial customers to declare that the electricity they are consuming is renewable.

Despite parallels and synergies between today's hydrogen industry and the solar and wind industries of the early 2000s, one key difference exists in the evolution of certification. When EACs for electricity were first introduced in 1997, mature electricity transmission and distribution infrastructures, regulations and use cases were in existence, none of which exist today for hydrogen.

The Arabian lights project: toward a regional role for Saudi Arabia

Saudi Arabia has launched several initiatives with the potential to shape certain segments of the emerging hydrogen supply chain. For example, the country has articulated and is championing a CCE framework, the centerpiece of its 2020 G20 presidency. CCE elements are prerequisites for producing low-carbon hydrogen and mitigating the accumulated atmospheric CO_2 emissions. In October 2020, the establishment of a dedicated fund to invest in the CCE was announced.

Saudi Arabia can leverage the CCE framework by positioning itself and the Middle East as a global CCUS hub. This hub would be able to capture, transport, utilize, store, and import CO_2 at scale cost-effectively (e.g., with a target capacity to store 50–100 mt/y). It could also create local ecosystems for CO_2 utilization supported by bidirectional supply chains linking the hub with end-use markets in major demand centers globally. The proposed CCUS hub would be named the Arabian Lights project (Figure 7.5) and could achieve several objectives:

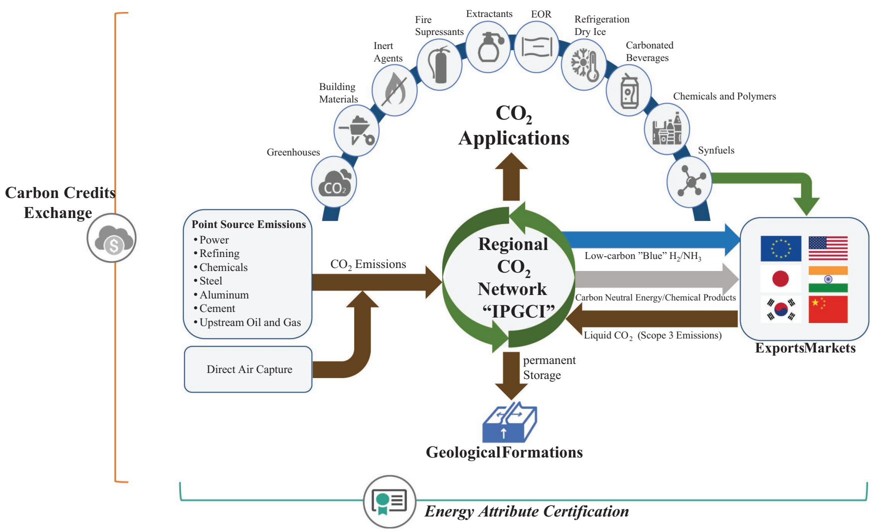

FIGURE 7.5 Arabian lights CCUS project framework.

1 Enable the scaling up of low-carbon hydrogen and ammonia production (referred to as CCUS-enabled hydrogen).
2 Incentivize investments in CCUS technologies and infrastructure.
3 Exponentially expand the CO_2 utilization market.
4 Maintain competitiveness when carbon border taxes are introduced (e.g., the EU's Carbon Border Adjustment Mechanism) via the supply of carbon-neutral synfuels and chemical products to end users worldwide.
5 Scale up the use of captured CO_2 in EOR, which would:

   - Maximize the recovery of oil reserves
   - Extend the life of its oilfields
   - Attain (potential) carbon neutrality for petroleum exports (provided a disproportionate amount of CO_2 is injected and retained for every barrel of oil recovered).

6 Play a proactive role in shaping a global carbon market.
7 Expedite the path toward reaching net-zero emission targets.
8 Transform the role of the private sector in the economy, potentially creating world-class carbon management companies that can compete globally.
9 Create job opportunities for its citizens in the emerging hydrogen and CCE economy.

CCUS hubs are proven mechanisms for accelerating the reduction of CCUS costs through economies of scale and standardization and incentivizing the decarbonization of existing fossil-based power and industrial plants. They also expand opportunities for CO_2 utilization. The Oil and Gas Climate Initiative (OGCI) (2022a) has identified 279 potential CCUS hubs in 56 countries, matching emission sources with possible storage locations, of which five with a CCS cost of less than \$100 per ton are located in Saudi Arabia. The largest of these five potential hubs is located close to the industrial cities of Jubail and Yanbu.

Eight conditions must be satisfied to transform this concept into a commercially viable project opportunity. Saudi Arabia and other GCC countries already satisfy the first three, whereas other regions and countries offer precedents for the remaining five (Table 7.11).

Except for the GCC Grid Interconnection Authority, headquartered in Dammam, Saudi Arabia, the track record of GCC member states partnering on energy projects has been weak. The Authority plays an instrumental role in creating a regional electricity market among member states and beyond. However, to avoid stranding a large proportion of their hydrocarbon reserves, they may be incentivized to pool their resources for the development of cross-border CCUS projects. Saudi Arabia is well positioned to spearhead and ensure support for the development of a regional CCUS hub and CO_2 shipping fleet.

TABLE 7.11 Arabian Lights project conditions

Condition	*State of play*
1 Geological formations suitable for large-scale carbon dioxide (CO_2) storage	The Global CCS Institute recently determined that subject to a technical appraisal, the Middle East may possess highly suitable geological basins for CO_2 storage (Minervini, Consoli, and Kearns 2021). Three types of geological reservoirs can be used for long-term CO_2 storage: deep saline formations, depleted natural gas reservoirs, and depleted oil reservoirs with potential for CO_2-enhanced oil recovery (EOR). The Middle East has up to 2,511 Gt CO_2 of storage capacity with a substantial amount within Saudi Arabia (UNIDO 2011). However, only 0.74 Gt have been assessed in Saudi Arabia (OGCI 2022b). Geological formations in central eastern Saudi Arabia are already used for CO_2 storage. Other suitable candidate sites are in the UAE and potentially in Kuwait, Qatar, Iraq, and Iran. There is no inherent seismic activity in most parts of the region. Furthermore, because of their level of maturity, substantial subsurface data exist for oil and gas reservoirs. In addition, an extensive pipeline infrastructure is already in place. ✓ A comprehensive CO_2 storage assessment should be conducted to identify and determine the suitability of geological formations. ✓ Investment in suitable CO_2 storage projects being developed in Europe and the United States is necessary.
2 Large CO_2 emission sources	Concentrated point source emissions from electric power, refining, chemical, cement, steel and aluminum plants are clustered in industrial and oilfield zones across the Gulf Cooperation Council (GCC). These are expected to reach 407 mt in 2025, with power generation being the largest emissions source (Qamar Energy 2021). Annual point source CO_2 emissions in Jubail and Yanbu industrial cities are estimated to be 75.5 mt and 22.5 mt, respectively (OGCI 2022b). Emissions from upstream oil and gas and mining operations in Saudi Arabia provide an additional and important source of emissions.
3 CO_2 transportation and utilization infrastructure	Carbon capture, utilization and storage (CCUS) technology requires an efficient infrastructure platform. It is relatively small but growing quickly. Transportation infrastructure is available to serve three carbon capture and storage (CCS) projects in the GCC, capturing 3.7 mt/y of CO_2 (Global CCS Institute 2020). Plans to capture a further 11 mt/y of CO_2 by 2026 in the GCC region have already been announced (Qamar Energy 2021).

Country	*Project*	*CO_2 source*	*CO_2 capture capacity*	*Primary storage/use*
Saudi Arabia (Saudi Aramco)	Uthmaniyah CCS-EOR	Natural gas processing	0.8 mt/y	EOR
UAE (AbuDhabi National Oil Company)	Al Reyadah CCS-EOR	Iron and steel production	0.8 mt/y	EOR
Saudi Arabia (Saudi Basic Industries Corporation; SABIC) *Note 1	Jubail CO_2-to-Chemicals	Chemicals production	0.5 mt/y	Methanol, urea, and food and beverage

(*Continued*)

TABLE 7.11 (Continued)

Condition	*State of play*				
	Qatar (QP)	CCS-EOR	LNG production	2.0 mt/y	EOR
	Saudi Arabia (Gulf Cryo)	Saudi Industrial Beverage Co.	Industrial boilers	0.1 mt/y	Food and beverage
	Kuwait (Gulf Cryo)	EQUATE CO_2 Recovery	Ethylene glycol production	0.05 mt/y	Food and beverage

**Note 1: In late 2020, Saudi Aramco established the supply of blue ammonia to Japan. The CO_2 captured from hydrogen production (which is used as feedstock for the Haber–Bosch ammonia synthesis) was used to produce methanol at SABIC's Ibn-Sina plant in Jubail Industrial City. It was also used for EOR at the Uthmaniyah oilfield. These projects are real-life examples of the CCE framework's implementation.*

Example: CO_2 uses in the GCC are diverse. They range from EOR to feedstocks for chemical and other industries and distribution to the food and beverage industry and recently, to greenhouses.

Condition	*State of play*
4 Business models	Business models must be developed for CCUS hub developers (e.g., emitters, transport and storage [T&S] operators, and traders). This will enable them to recoup their capital investment and operating expenditure. Moreover, they will be able to earn a suitable return on investment from projects across the CCUS supply chain, including cross-border CO_2 transportation projects. Emitters would need to generate revenue streams to cover the investment for capture, purification, and compression, and T&S operating expenses are typically paid to an operator. T&S operators are paid to transport and store CO_2 emissions via a tariff that covers their investment and operating costs and provides a return on investment. CCS-as-a-service business models are among the innovative approaches being developed. At the outset, business models must **integrate low-carbon hydrogen production** into their designs. They must also identify and mitigate the commercial, technology, financing, and regulatory risks across the CCS supply chain. Furthermore, they must enhance the commercial viability of projects. This would include the interdependency between the supply chain elements (technology, sources, pipelines, and sinks) and long-term storage liability, with insurance against leakage. A global CO_2 value chain cost model should be built to evaluate the economic viability of importing Scope 3 CO_2 emissions from industrialized countries for permanent storage and utilization. All supply chain costs including capture, compression, and dehydration, transportation, injection (EOR), permanent geological storage, and monitoring and verification must be covered. **Example:** In partnership with Japanese and Korean firms, **Saudi Aramco** is evaluating the feasibility of using LPG as a hydrogen carrier. It is also assessing the viability of the transportation of CO_2 produced at destination markets back to Saudi Arabia.
5 National regulatory framework	Creating a regulatory and policy framework to incentivize investment across the CCUS supply chain and enable business models is essential. Many policy mechanisms are already provided by the governments in Australia, the EU, the United States, and the United Kingdom to support CCS projects. These policy mechanisms include capital grants for feasibility studies and first-of-a-kind projects as well as investment and production tax credits. They also comprise contracts for difference to enable emitters to cover the cost of capture and regulated T&S tariffs for an open-access T&S infrastructure. Other policy mechanisms include public procurement, industry standards, verifiable CCUS credits, and CCUS infrastructure funds.

(*Continued*)

TABLE 7.11 (Continued)

Condition	*State of play*
	To ensure that CO_2 is stored in an environmentally safe and transparent manner, clearly defining long-term liability provisions among CCUS supply chain actors is necessary. For GCC countries in which EOR is a major CO_2 utilization route, additional revenues from increased oil production could be earmarked for CCS investments.
6 Regional regulatory umbrella	A variation of the European Commission's framework **Important Projects of Common European Interest (IPCEI)** should be implemented for GCC member states. An IPCEI approach is needed to incentivize cross-border investment in regional CCUS projects by governments, national oil companies (NOCs), and state-owned and private enterprises. This is to attain economies of scale and pool human, capital, technical and geological resources in a cost-efficient manner. Such a framework would facilitate the following: 1 Structuring of commercial public/private partnership frameworks for private sector bidding to develop regional CO_2 storage sites and providing economic incentives for both host governments with bidding consortia; 2 Issuance of climate and/or green bonds to finance CCUS infrastructure and projects potentially backstopped by sovereign guarantees; 3 Treatment of avoided CO_2 emissions under each country's respective Nationally Determined Contributions (NDCs). **<u>Example</u>:** In the EU, IPCEI are eligible for funding from the €30 billion **Connecting Europe Facility**. This is an effective tool for developing key energy infrastructure projects aimed at creating an integrated European energy market.
7 Large-scale cross-border CO_2 shipping industry	A CO_2 shipping company owned by GCC member states, via either their NOCs or sovereign wealth funds, should be created. The large-scale shipping of CO_2 is in its infancy. Small-scale ships (800–1,800 m^3) are usually used to transport CO_2, catering primarily to the food and beverage industry. CO_2 ships operating at scales suitable for CCS have not yet been developed. However, CO_2 ships and terminals are expected to benefit from the in-depth experience of the liquefied natural gas (LNG) and liquefied petroleum gas (LPG) industries. Saudi Aramco is evaluating the conversion of LPG ships to handle liquid CO_2 cargo. However, the volumes involved will not be sufficient to cover the large amounts of CO_2 that could be imported. The technology readiness level for CO_2 shipping ranges from 3 to 9 (Global CCS Institute 2021). **<u>Example</u>:** Several shipping companies have started to develop large-scale liquefied CO_2 ships. These include **Mitsui O.S.K.** Lines (Japan) and **Larvik Shipping** (Norway).
8 Carbon markets	Carbon markets should be developed over two phases. In the first phase, a voluntary market should be created by building demand and supply. In the second phase, a compliance market should be established via a regulated cap-and-trade system. The first would incorporate both carbon credits (ex-ante instruments) and energy attribute certificates or renewable energy certificates (ex-post instruments): **a** This would involve trading and retiring CCUS-related credits (e.g., CO_2 reduction, removal, and potential storage) backed by robust carbon accounting methodologies approved by carbon credit standard-setting bodies. These credits would assist in financing otherwise unviable projects.

(*Continued*)

TABLE 7.11 (Continued)

Condition	*State of play*
	b Energy attribute certification schemes will need to be developed for carbon removal and reduction. These would measure the lifecycle greenhouse gas emissions of CCUS and CCUS-enabled hydrogen projects to establish that the captured CO_2 is being sequestered or utilized sustainably. Such certification schemes may integrate carbon credits into their design to offset residual emissions that could not otherwise be abated.
	The carbon market and its instruments must eventually be consistent with Article 6 of the Paris Agreement (including the planned use of the International Transfer Mitigation Outcomes). This would allow them to be used in NDCs and facilitate international carbon trade.
	Example 1: Two initiatives aimed at creating a voluntary carbon market in the Middle East were recently announced. First, the **AirCarbon Exchange** was launched at the Abu Dhabi Global Markets in Abu Dhabi (AirCarbon 2022) and second, a carbon exchange platform backed by the **Public Investment Fund**, **Aramco**, **ACWA Power**, **Saudi Airlines**, **Ma'aden**, and **Enowa**, a NEOM subsidiary, will be established in Saudi Arabia (MSN News 2022).
	Example 2: KAPSARC has proposed tradable carbon sequestration units, a verified ton of CO_2 securely stored in geological formations (KAPSARC 2022).

Source: Author.

Conclusion

Hydrogen investments provide MENA countries with a tangible opportunity to assume a proactive role in their ongoing energy transition. Energy-exporting countries can act as global energy suppliers, prevent their hydrocarbon assets from becoming stranded and reorient their economies and social contracts toward the emerging energy paradigm. For energy-dependent countries, such investment would help make their chemical, fertilizer and manufacturing industries self-sufficient and even reposition some of them as energy suppliers.

In response, several early movers, including Egypt, Morocco, Oman, Saudi Arabia, and the UAE, have already begun to develop renewable and low-carbon hydrogen and ammonia projects. They have prepared hydrogen strategies and roadmaps and entered into collaborative agreements with industrial countries. A total of 47 projects at a cost of $55 billion were announced by the end of 2021. However, MENA countries experience numerous mindset, industry, regulatory, and institutional challenges to capitalize on this narrow window of opportunity for renewable and CCUS-enabled hydrogen. With pressure on countries, companies, and individuals to target net-zero carbon emissions by 2050, a key concern for MENA energy suppliers is capturing a sizable global energy market share.

To overcome these challenges, MENA countries must undertake the following actions. First, they must invest across the hydrogen and CCUS supply chains, including in hubs, use cases, and applications in European, Asian, and North

American demand centers. Second, they must develop local ecosystems and industry clusters to lower the LCOH and create applications in the electricity, industry, and mobility sectors. Third, they must provide subsidies and grants to projects and consumers to de-risk hydrogen production, incentivize demand uptake, enhance bankability and include funding in public budgets. Fourth, they must create overarching and enforceable regulations to govern the entire energy sector and create a level playing field for all industry stakeholders. Fifth, they must engage with governments in major demand centers over regulations, including certification schemes, to ensure fair treatment and reciprocity. Sixth, they must incentivize industrialized countries to channel a proportion of their funds earmarked for export promotion toward developing the local ecosystem and demonstrating pre-competitive technologies. Seventh, they must finance key enabling technologies to reduce water consumption and lower the LCOH of cross-border hydrogen and derivatives transportation. Moreover, they need to reduce carbon production pathway emissions and exploit sour gas reserves. Eighth, they must strengthen the local private sector's (including SMEs) project development capacity for it to lead in renewable hydrogen and CCUS project development at home and abroad. Allowing international developers, industrial gases, and oilfield service companies to dominate the development of renewable hydrogen projects or provide CCUS-related services would diminish national competitiveness.

Notwithstanding the Ukraine crisis, the energy transition is likely to resume if not accelerated its pace in the affected energy markets. During this period, MENA exporters will reap substantial and previously unbudgeted windfall revenues created by high crude oil and LNG prices. These accumulated revenues will eliminate any doubts about MENA countries' capacity to fund their market entry strategies into the emerging hydrogen and derivative market. MENA NOCs, SWFs, and private developers will also be able to compete with energy majors for the mergers and acquisition opportunities likely in the hydrogen space. This would enable them to develop new competencies and improve market access.

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8

EUROPE’S HYDROGEN PATHWAYS

Toward a balanced partnership with Saudi Arabia and the Gulf

Jan Frederik Braun, Ad van Wijk, and Kirsten Westphal

Introduction

Compared with other regions globally, Europe has formulated the most comprehensive policy framework to achieve its hydrogen ambitions and advance its hydrogen development trajectory.[1] The continent has the dual aim of becoming a global clean hydrogen leader and fueling its decarbonization efforts. Hence, the European Union (EU) is aiming to incorporate a large proportion of low-carbon and renewable hydrogen into the continent’s energy mix by 2030. Moreover, Russia’s unprecedented invasion of Ukraine in early 2022 turbocharged the EU’s energy transition ambitions, radically shifting its willingness to depend on any singular fossil fuel exporter. Shortly after Russia’s act of war, the European Commission (2022a) proposed a Hydrogen Accelerator as part of the REPowerEU plan, with 10 Mt produced in the EU and 10 Mt of imports.

Prominent scenarios that project the supply of and demand for renewable hydrogen and its derivatives by 2030 highlight the imbalance between these two variables (Breitschopf et al. 2022). These supply gaps in 2030 must be covered by imports from outside the EU. However, current hydrogen imports from outside the EU are almost non-existent. Indeed, less than 90 tons was imported in 2020, of which two-thirds came from Switzerland (Hydrogen Europe 2021). In short, producing 10 Mt domestically and importing another 10 Mt of renewable-based hydrogen by 2030 is a hyper-ambitious challenge. Meeting this challenge will require massive investment throughout the value chain and international cooperation, including with major fossil fuel and (projected) hydrogen exporters in the Gulf region such as Saudi Arabia.

While Gulf players are long-standing energy partners for Europe, the EU is aiming to strengthen its strategic relationships with them to realize REPowerEU.

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Gulf countries have the capacity and know-how to produce renewable-based and low-carbon hydrogen (and derivatives) and now have the additional geopolitical and climate incentive to position themselves as reliable providers of clean energy imports for Europe. In turn, EU policymakers have taken a front-and-center position in shaping standards and setting up certification schemes. Likely to become a critical future import market, the European Commission is seeking to denominate the global price of hydrogen in Euros and propose the currency as an international benchmark as the market expands (IRENA 2022). This is a win/win for Europe's hydrogen leadership ambitions, as the continent is the world's largest geographical market for electrolysis, with over a third of the global announced capacity (Hydrogen Council 2023).

On the surface, Europe's hydrogen approach under REPowerEU seems coherent. It is driven by a shared ambition to become the world's industrial leader in renewable hydrogen while fueling the continent's decarbonization efforts. Beneath the surface, however, Europe's national and supranational hydrogen pathways are marked by incompleteness of legislative action, resulting in discord between Europe's supranational hydrogen ambitions and the required fast implementation of European legislation at the national level. Other issues include the incoherence of regulatory approaches supporting a European market for hydrogen and coordinated development of storage, pipeline facilities, and port infrastructure. There are also differences between countries. Some nations are against hydrogen imports and instead focus on local production and demand. Meanwhile, some have adopted an international, pan-European, import-oriented vision. Lastly, the hydrogen color debate is ongoing. Most countries favor a focus on renewable-based (or 'green') production and have prematurely excluded technological routes related to natural gas and carbon capture, utilization, and storage (CCUS) (blue) as a temporary solution that could be more carbon-effective. Prospective exporters therefore assume Europe will not accept deals for anything other than green hydrogen. However, with strong methane controls and world-leading carbon capture and storage (CCS), fossil fuel-derived hydrogen can also be low-emission hydrogen. This hydrogen can be produced and scaled at a much cheaper rate in fossil fuel-rich regions such as the Gulf (Azadegan and Tovar 2022; IPCC 2022). These factors make Europe a complicated partner and a complex future import market for ambitious hydrogen exporters such as Saudi Arabia and the Gulf region at large.

This chapter provides an overview of and insights into Europe's hydrogen pathways. It discusses how the continent must quickly establish a balanced import strategy that features renewable and low-carbon hydrogen. The main messages of the chapter are as follows:

- The key focus in Europe toward 2030 is on scaling electrolyzer manufacturing capacity, decarbonizing hydrogen use in industry, promoting hydrogen in new use cases, and building the transport infrastructure, including storage facilities.

- The EU and national governments are focusing on renewable hydrogen. This is giving prospective exporters the impression that the continent will not accept deals for anything other than that. However, several countries such as the United Kingdom and the Netherlands are taking a more technology-neutral approach toward hydrogen. Further, large consumers such as the Port of Rotterdam intend to accept various production methods so long as the fuel is low carbon.
- Europe is broadly focusing on eliminating carbon emissions in the medium-to-long term. Saudi Arabia's Circular Carbon Economy (CCE) approach is focusing on commodifying carbon emissions. Its aim is to reframe the discourse on CO_2 from being viewed solely as a negative externality to recognizing the value that can be extracted from it. These different sustainability approaches and their end goals must be reconciled in a collaborative policy approach, preferably as part of the EU's Strategic Partnership with the Gulf.
- The EU must present a long-term roadmap for hydrogen imports from the Gulf region that departs from a balanced strategy between renewable-based and low-carbon hydrogen. This should include coherent and full-fledged support for a continued pathway for the production and sale of hydrocarbons from Saudi Arabia and the Gulf region at large. Such production must be in an environmentally sound manner. For example, by using harmonized certification and strict CCUS rates, including near-zero upstream methane emissions.

The remainder of the chapter is organized as follows. The second section consists of a two-part analysis. The section first examines the EU's strategic action on hydrogen. The EU is a treaty-based organization that can only act within the limit of the competencies conferred to it by its member states; hence, energy policy is a shared competency. The second part examines the national hydrogen approaches in several key European countries since EU members have the right to determine their national energy mix and conduct bilateral energy relations with non-EU countries. The third section presents hydrogen applications across Europe. The fourth section assesses European research and innovation (R&I) with a focus on hydrogen technologies. The fifth section presents a case study of the EU's hydrogen corridor approach and the opportunity this initiative offers Saudi Arabia. The final section concludes.

EU and national hydrogen strategies

Europe is the world's leading hydrogen region in terms of the comprehensiveness of its policy packages and combination of technology push, demand-pull, and fiscal policies (Figure 8.1).

The strategies and policy packages analyzed here provide substantial funding to kickstart the scaling of hydrogen production and clusters or 'valleys' of large-scale demand. In parallel, offtake and utilization in end-use sectors are

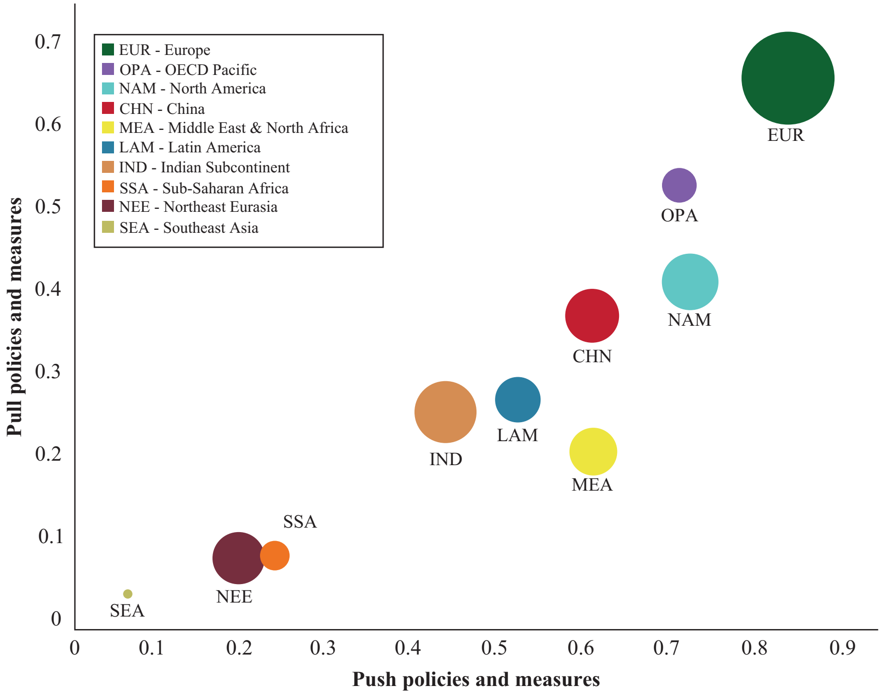


FIGURE 8.1 Clean hydrogen production by 2030: regional targets and policy comprehensiveness.

Source: Jan Frederik Braun and Linah Al Hamdan based on DNV (2022).

Notes: This figure represents the percentage total score (0.1–1) given to each region in the categories push and pull policies and measures across the X- and Y-axes. The bubble size represents the regional hydrogen production targets by 2030 (renewable or low carbon). Push policies and measures include technology evolution and R&D (e.g., renewables procurement) and standards and certification (e.g., certificated of origin). Pull policies and measures include markets and financing (e.g., carbon pricing, fiscal incentives) and matching supply and demand (e.g., supply quotas, public tenders). The total score was taken before the United States Senate passed its landmark IRA in August 2022. The IRA includes an unprecedented tax credit for clean hydrogen production.

stimulated (e.g., proposed legally binding targets and obligations on fuel suppliers). Cost competitiveness against conventional fossil fuel-based technologies is advanced by tightening carbon pricing (e.g., including more sectors and removing exemptions). It is also helped by international initiatives such as the Global European Hydrogen Facility, which aims to create a level playing field between EU and non-EU suppliers.

The **EU Hydrogen Strategy (2020)** (Figure 8.2) aims for at least 40 GW of electrolyzer capacity installed by 2030. The strategy's main priority is to develop renewable hydrogen (European Commission 2020a). In the short-to-medium term, however, other forms of low-carbon energy are needed to rapidly reduce emissions from

FIGURE 8.2 The EU hydrogen strategy.

Source: Informaconnect (2020).

existing hydrogen production and support renewable hydrogen's parallel and future uptake. Low carbon encompasses fossil fuel-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas (GHG) emissions than existing hydrogen production (European Commission 2020a).

Like most government strategies in Europe, the EU Hydrogen Strategy recognizes three stages of hydrogen development (European Commission 2020a):

- Scaling up and laying the market foundations (early 2020s).
- Pursuing widespread adoption and market maturity (late 2020s and early 2030s).
- Fully implementing hydrogen as a clean energy vector (after 2030).

The strategy focuses on two end-use sectors: industry and transport. An immediate application in industry is to reduce and replace carbon-intensive hydrogen in refineries, ammonia production, and methanol production as well as replace fossil fuels in steelmaking. In the second phase from 2025 to 2030, the strategy states that hydrogen can form the basis for investing in and constructing zero-carbon steelmaking processes in the EU. In transport, it proposes the early adoption of hydrogen in aviation, shipping, and long-haul transport; road transport such as city buses and taxis; and specific parts of the rail network in which electrification is not feasible.

In 2021, EU member states formally adopted the **EU Climate Law**. The Law sets the binding objective of reducing GHG emissions by 55% by 2030 (compared with 1990 levels) and climate neutrality (or net-zero emissions) by 2050. In turn, the Climate Law has set the stage for the EU's **Fit for 55 legislative package parts I and II (2021). These measures promote emissions reductions by increasing demand for and the production of renewable and low-carbon hydrogen across the EU economy.**

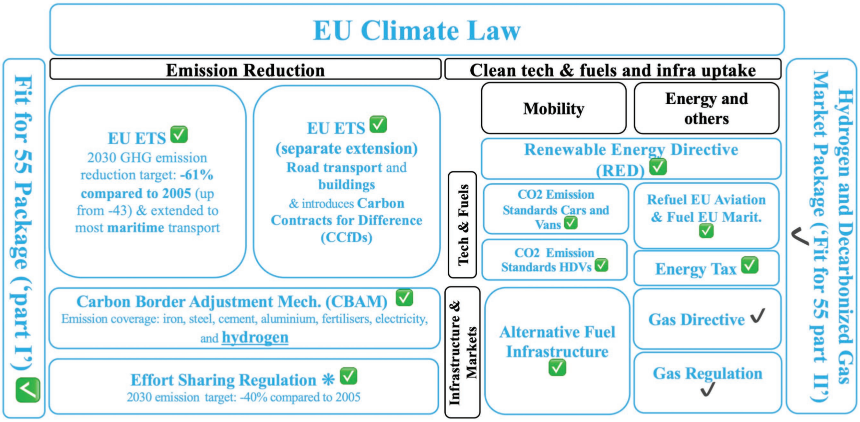


FIGURE 8.3 EU energy and climate legislative acts relevant to the EU hydrogen 'ecosystem'.

Source: Jan Frederik Braun adapted from Hydrogen Europe (2021).

Notes: Effort sharing sets binding targets for reducing GHG emissions in sectors outside the EU Emissions Trading System (ETS). Due to limited space here, effort sharing is not included in the analysis here.

Figure 8.3 summarizes the EU's energy- and climate-related legislative acts and revisions with the highest potential impact on the hydrogen market.

'Fit for 55 part I' indirectly reinforces the incentives for member states to support renewable hydrogen by setting new and increased national targets for specific sectors' consumption:

- From the end of 2023 onward, the **Carbon Border Adjustment Mechanism (CBAM)** will be set up to equalize the price of carbon paid for EU products operating under the EU Emissions Trading System (ETS) and the one for imported goods. This will be achieved by obliging companies that import into the EU to purchase so-called CBAM certificates to pay the difference between the carbon price paid in the country of production and the price of carbon allowances in the EU ETS.[2] CBAM will cover iron and steel, cement, aluminum, fertilizers, and electricity (European Parliament 2022). From 2026, imports of hydrogen into the EU will be subject to an adjustment based on their carbon content (European Commission 2023a). Additionally, the EU plans to 'lead efforts for developing a solid framework for a global rules-based and transparent hydrogen market' (European Commission and High Representative of the Union for Foreign Affairs and Security Policy 2022a). This could be translated into a plan by the EU to implement certification processes with future exporting countries to ensure that hydrogen imports are produced to the same standards as the renewable hydrogen produced domestically (Alsulaiman 2023).

- The amended **Renewable Energy Directive (**or **RED)** states that by 2030, 42% of the hydrogen consumed in the industry should be green and that this proportion is set to rise to 60% by 2035 (European Commission 2021a; European Parliament 2023). The EU's **Hydrogen Delegated Acts (2023)**, which supplement RED, outline the conditions that a hydrogen project developer would need to meet to classify the power used for hydrogen production as renewable. The delegated act states that its scope includes hydrogen produced both inside and outside of the EU, meaning international market participants seeking to contribute to REPowerEU's target of 10 Mt of renewable hydrogen imports by 2030 will need to adhere to the delegated act. Annex 1 describes the rules for producing renewable hydrogen in the EU, which gives European and global hydrogen market participants the highly-anticipated clarity required for bringing the hydrogen market forward.
- **Refuel EU Aviation** promotes sustainable aviation fuels (SAFs), which can take the form of power-to-liquid, and synthetic fuels such as kerosene. Airline operators and fuel suppliers must ensure increasing levels of SAFs with minimum proportions of synthetic aviation fuels in jet fuel from 2025 onward (European Commission 2021b) (Figure 8.4).
- **Refuel EU Maritime** sets a maximum limit on the GHG content of energy used by ships calling at European ports with the reduction targets shown in Figure 8.5. These targets incentivize the uptake of low-carbon and clean hydrogen in the maritime sector.

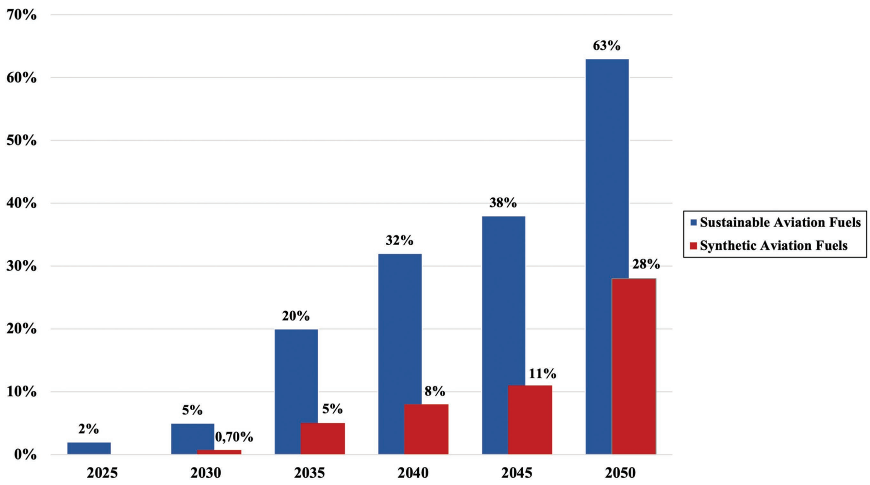


FIGURE 8.4 Minimum levels of the sustainable and synthetic aviation fuels required in jet fuel.

Source: Jan Frederik Braun based on Refuel EU Aviation. *Source:* European Commission (2021b).

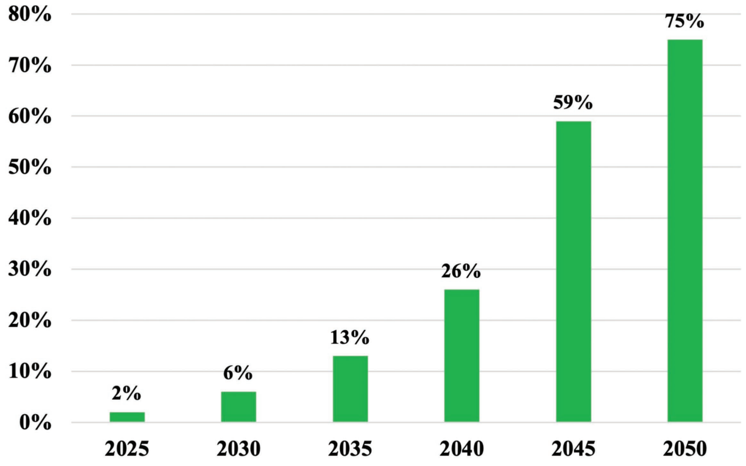


FIGURE 8.5 Reduction targets for GHG emissions for ships calling at European ports.

Source: Jan Frederik Braun based on European Commission (2021c).

- The **Revised Alternative Fuels Infrastructure Directive** calls for hydrogen refueling stations at least every 150 km on highways for compressed hydrogen and every 450 km for liquid hydrogen by 2030 (European Commission 2021d).
- The amendment of the regulation setting **CO_2 emissions standards for cars and vans** establishes an EU fleet-wide target to reduce the CO_2 emissions produced by new passenger cars and light commercial vehicles by 100% by 2035 (compared to 2021) and mentions hydrogen as a decarbonization option for heavy-duty vehicles (European Commission 2021e).
- The **Revision of the Energy Tax Directive** establishes preferential tax rates for using green and low-carbon hydrogen for end consumers, which may also explicitly incentivize hydrogen uptake in maritime and aviation transport (European Commission 2021f).
- The **EU Emissions trading system (ETS)** introduces Carbon Contracts for Difference. These contracts aim to ramp up clean hydrogen demand in industrial plants by funding projects that produce clean hydrogen at a premium to cover the cost gap between the ETS CO_2 price and breakeven production cost (European Commission 2021g).

The implementation of Fit for 55 part I will have massive implications for Saudi Arabia and the Gulf countries in several ways. First, it heralds the overall end of the fossil fuel era in the EU as the package sets ambitious and binding targets for the phase-out of fossil fuels in key sectors like industries, transport, and electricity. Second, both domestic and third-country producers will need to comply with the EU's requirements formulated as part of CBAM and the

Delegated Acts for producing clean hydrogen. This will incentivize the Gulf and other non-EU countries to produce clean hydrogen according to the EU's strict carbon policies or otherwise be excluded from this major and highly lucrative export market.

The **Hydrogen and Decarbonized Gas package**, or '**Fit for 55 Part II**', aims to regulate the transmission and distribution of renewable and low-carbon hydrogen. One objective is to facilitate the emergence of an open and competitive EU hydrogen market, including non-EU countries. Another is to ensure access to renewable gases based on an EU-wide certification system to ascertain their carbon content. The package strives to gradually phase out natural gas assets, avoiding stranded costs, wherever electrification or switching to renewable or low-carbon gases is possible. To prevent the lock-in of natural gas, long-term gas contracts should not extend beyond 2049 (European Commission 2021h).

Like the EU Hydrogen Strategy, the package recognizes the short- and medium-term role of low-carbon hydrogen in reducing emissions of existing fuels and supporting the uptake of renewable hydrogen. To support this, it aims to create a certification system for low-carbon gases according to a life-cycle assessment of GHG emissions, thereby supplementing the certification of renewable gases under Fit for 55 Part I.

Russia's war against Ukraine has caused a tectonic geopolitical shift in Europe similar to the fall of the Berlin Wall in 1989, thereby turbocharging the EU's energy transition. In response, the European Commission has formulated **REPowerEU**. This revised EU energy security strategy boosts the aims and targets of 'Fit for 55' to achieve independence from Russian fossil fuels well before 2030. It consists of three pillars to increase the resilience of the EU energy system:

- Diversifying gas supplies using LNG and pipeline imports from non-Russian suppliers as well as biomethane.
- Incepting a Hydrogen Accelerator that targets production and imports of 20 Mt by 2030.
- Reducing faster the EU's dependence on fossil fuels by boosting energy efficiency gains, increasing the share of renewables, and addressing infrastructure bottlenecks.

REPowerEU envisages an almost fourfold increase in the production and import of hydrogen compared with the Fit for 55 package, from 5.6 Mt to 20 Mt by 2030. As noted earlier, this will be split equally between domestic renewable hydrogen production and imports by 2030 (European Commission 2022a). Based on the expectation that supply capacity for transporting hydrogen into Europe is established, REPowerEU assumes 6 Mt will be imported via pipeline as hydrogen and 4 Mt as ammonia or other hydrogen derivatives, probably imported by ship (European Commission 2022b; Lambert 2022).

With the focus of hydrogen demand remaining on applications in hard-to-decarbonize sectors in industry and transport, REPowerEU:

- Increases hydrogen demand by ramping up mandatory obligations for industry and transport and focusing on conversion-per-geographical areas by drastically increasing the number of 'hydrogen valleys' in Europe by 2025.
- Creates an EU Energy Platform for the voluntary joint purchasing of hydrogen. In turn, this platform operationalizes the Global European Hydrogen Facility, which draws on the architecture of the German 'H2Global' instrument (Box 1). Furthermore, the Global European Hydrogen Facility facilitates the domestic production and EU import of green hydrogen by developing a robust regulatory framework and standards as well as coordinating EU-wide projects.
- Establishes Green Hydrogen Partnerships that promote the import of renewable hydrogen from third countries while incentivizing usage and decarbonization domestically and a dialogue on standards and certification.

BOX 8.1 THE H2GLOBAL INSTRUMENT

H2Global is an instrument for a quick and effective hydrogen or power-to-X market ramp-up at an industrial scale. This instrument aims to accelerate production and imports, thereby strengthening the creation of a sustainable hydrogen market and the EU's energy sovereignty.

How does it work? In the absence of pricing signals, an intermediary (in this case, the Hintco) concludes long-term purchase contracts on the supply side and short-term sales contracts on the demand side for sustainably produced green hydrogen and its derivatives. The intermediary is backed by government support (in this case, the German government) that provides these long-term offtake contracts and investors with the necessary investment security and bankability to finance the projects. Shorter-term sales contracts are concluded on the demand side. Pricing on the purchase and sales side is carried out through a competition-based bidding process ('double auction mechanism'). In compliance with predefined (sustainability) criteria based on the existing EU regulatory framework for the production and transport of the products, the lowest bid price, or the largest quantity and highest sales price in Europe, will be awarded the contract. Short-term sales contracts make it possible to reflect the expected increase in the willingness of buyers to pay and thus in the market prices for the energy sources. The divergence in the tenor of the purchase and sales agreements creates a symmetric market premium instrument, which is highly efficient and market-based. This means that the difference between procurement costs and resale revenues to be compensated with public funds is minimized (Figure 8.6).

FIGURE 8.6 The H2Global Instrument.

Source: www.h2-global.de (2022).

- Accelerates the creation of the required hydrogen infrastructure and storage capacity across the EU and identifies a limited number of hydrogen import pipelines. Three hydrogen priority corridors could allow for importing 10 Mt of renewable hydrogen. This includes one in the Mediterranean, which will feature Greece as a central hub. Saudi Arabia declared Greece a strategic hydrogen partner in 2022 (Chatzimarkakis 2022).

The EU's **Strategic Partnership with the Gulf (2022)** is formulated in the context of realizing REPowerEU, as it (European Commission and High Representative of the Union for Foreign Affairs and Security Policy 2022b):

- Recognizes the Gulf region's prominent role as a producer and supplier of decarbonized energy and utilizes methane emissions reduction as a potential area of cooperation with the EU.
- Explores opportunities for production and trade to enable undistorted imports of renewable hydrogen (by building on existing projects in the Mediterranean region).
- Aims to establish an integrated gas and hydrogen infrastructure, hydrogen storage facilities, and port infrastructure (i.e., through Green Hydrogen Partnerships).

Figure 8.7 summarizes the set-up and aim of REPowerEU and hydrogen cooperation with Gulf countries. This intends to provide a level playing field between EU production and third-country imports.

The EU is focusing on scaling renewable hydrogen production while low-carbon hydrogen is recognized in the transitional phase. Its key focuses for 2030

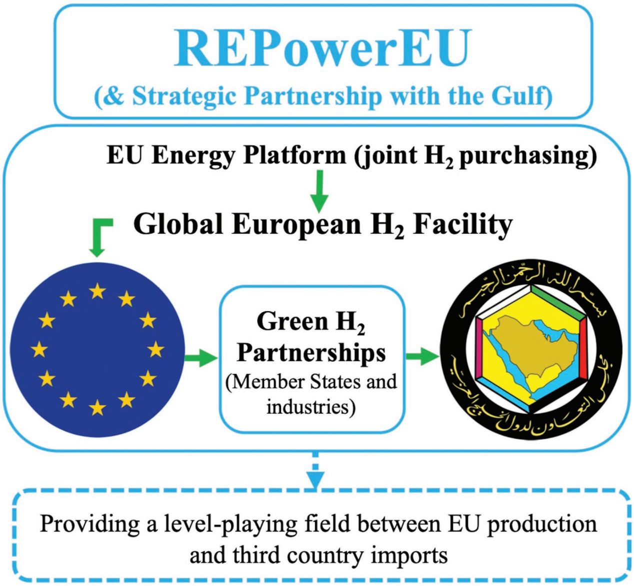


FIGURE 8.7 REPowerEU and a strategic partnership with the Gulf.

Source: Jan Frederik Braun based on European Commission and High Representative of the Union for Foreign Affairs and Security Policy (2022B).

are accelerated efforts in scaling up electrolytic hydrogen production capacity and integrated infrastructure and storage planning to decarbonize existing use in industry and promote new use cases. Establishing a joint auction-based approach for EU hydrogen and derivatives imports is emphasized.

REPowerEU has scaled-up Fit for 55 hydrogen targets for industry and transport. It has also communicated the need to define renewables-based hydrogen and address missing standards for hydrogen production, infrastructure, and end-use applications. Although the 10-Mt import scenario has many variations, a massive amount of additional solar and wind capacity is needed, together with about 350 GW of electrolyzer capacity (Van Wijk, Westphal, and Braun, 2022). If all the planned electrolytic hydrogen projects are carried out, around 118 GW of water electrolysis capacity would be installed by 2030—less than half the required 350 GW (Hydrogen Europe 2021). Table 8.1 presents a feasible high-level scenario for meeting the 20-Mt target.

To achieve REPowerEU's 20 Mt target by 2030, additional tools and actions that allow the EU's common hydrogen system to be bootstrapped are needed. This bootstrapping focuses on solving the chicken-and-egg dilemma, as it temporarily decouples supply and demand. This short-term decoupling then allows suitable infrastructure and storage facilities to be established to balance supply and demand and create a strategic reserve (Van Wijk, Westphal, and Braun 2022). A public/private

TABLE 8.1 A 2030 scenario for producing 20 Mt of green hydrogen (10 Mt in the EU and 10 Mt imported)

	*2*10 Mt Green hydrogen*	*Renewable resource*			*Electrolyzer*		*Hydrogen production*	
	2030	Capacity	Full load hours	Electricity production	Capacity	Full load hours		
		GW	*hr/yr*	*TWh*	*GW*	*hr/yr*	*Mt*	TWh_{HHV}
	EU production							
1	Offshore	30	5.000	150	30	5.000	3	118
2	Onshore wind	35	3.000	105	30	3.400	2	79
3	Solar PV	150	1.500	225	125	1.750	4	158
4	Grid-connected electrolyzers	Renewable/nuclear electricity from grid			7	7.000	1	39
	Import							
5	Onshore wind	30	3.500	105	25	4.100	2	79
6	Solar PV	150	2.100	315	115	2.650	6	237
7	Offshore wind	10	5.000	50	10	5.000	1	39
8	Hydropower/ nuclear	8	6.000	51	8	6.000	1	39
	TOTAL				**350**		**20**	**788**

Source: Van Wijk, Westphal, and Braun (2022).

financing scheme within the Global European Hydrogen Facility should be dedicated to building and repurposing transport infrastructure and storage facilities, especially for importing hydrogen. The latter requires an intercontinental and cross-border offshore transport infrastructure of pipelines and shipping routes. Further, a European Hydrogen Bank aims to unlock private investments in hydrogen value chains in the EU and in third countries by connecting renewable hydrogen supply with the emerging demand by European off takers (European Commission 2023a). By providing tools such as an EU-wide auction mechanism while aiming to increase transparency on transactions and prices, the strategy behind the Hydrogen Bank is to cover and, eventually lower, the cost gap between renewable hydrogen and the fossil fuels it can replace (ibid.). The US Inflation Reduction Act (IRA), which includes a generous tax credit of up to $3 per kilo of hydrogen production for a period of ten years (see Chapter 10), has forced the EU to reconsider its initial complex and non-competitive regulatory approach. The US' new climate mandate can herald a cycle of competition in clean energy technologies that could accelerate decarbonization. The initiative to establish the H2Global instrument an integral part of the European Hydrogen Bank and making this open to all EU governments interested in setting up hydrogen tenders and a joint European auction is a step in the right direction in making a tangible contribution to accelerating international hydrogen imports (European Commission 2023b).

With hydrogen demand in Europe of around 8.4 Mt (or 277 TWh) in 2019, all projections show massive increases by 2050 (Figure 8.8).

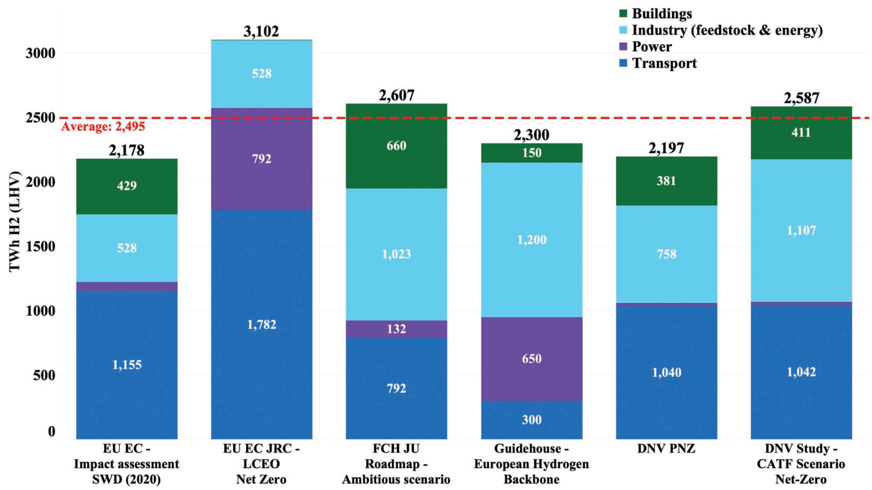


FIGURE 8.8 European hydrogen demand by 2050 (TWh/year).

Source: Jan Frederik Braun based on Azadegan and Tovar (2022).

The EU had reduced emissions by 24% by 2019 compared with 1990 levels, leaving it minimal time to achieve a 55% reduction in emissions by 2030 (European Commission 2022c). Within the EU, hydrogen produced by electrolyzers powered by renewable energy remains the primary focus. Simultaneously, Europe is in a race to build renewables sufficiently quickly so as to decarbonize the electricity grid. This means that it will not have the additional renewable electricity needed to produce significant volumes of green hydrogen in the near term. Fundamentally, difficult-to-electrify sectors such as heavy industry and heavy-duty transport will require a new set of low-carbon fuels such as hydrogen and ammonia to replace the fossil fuels used today. They will also need CCS to eliminate excess emissions. In sum, combining blue and green hydrogen is likely to be necessary to meet European demand toward 2030 and until the mid-century.

The Strategic Partnership with the Gulf is an essential first step toward recognizing the region as a critical contributor to the EU's 10 Mt import target and as a cooperation partner throughout the hydrogen value chain. Simultaneously, this chapter argues that the EU's focus on importing renewables-based hydrogen is one-sided, as it neglects the importance of a more balanced approach between renewables and low-carbon hydrogen. This is for Europe's own sake and that of Gulf countries.

Gulf states face twin challenges: on one side, moving to a more sustainable growth model that is less dependent on hydrocarbons and able to provide valuable jobs for their citizens; on the other, managing the transition to a global low-carbon economic environment that could significantly reduce energy revenues in the long term (Al-Tamimi 2022). As noted earlier, Saudi Arabia and other Gulf players are long-standing energy partners and have the capacity and know-how to produce low-carbon hydrogen and ammonia. Next to moving to a more sustainable growth model domestically, they now have the additional geopolitical and climate incentive to position themselves as reliable providers of clean energy imports for Europe. Simultaneously, the clean hydrogen 'window of opportunity' allows the Gulf countries to move toward a sustainable growth model that is less dependent on hydrocarbons and their governments manage the transition to a global low-carbon economic environment that could significantly reduce energy revenues in the long term. Policymakers in Brussels can thus shape the global market for low-carbon hydrogen and secure long-term supplies worldwide—a win/win for energy security and climate policy (Azadegan and Tovar 2022). However, hydrogen can only be considered a viable option for Europe when appropriate climate controls such as solid methane management and significant CCS are installed. Further, the details of what constitutes low-carbon hydrogen are lacking from the EU's Hydrogen Strategy and Hydrogen and Decarbonized Gas Package. The latter package must therefore lay out the terms to ensure that hydrogen imports do not adversely impact the climate.

No effective certification system for low-carbon hydrogen yet exists, and the Commission plans to introduce one in 2024. That is far too late. Many member states have already secured import deals and are adopting their schemes, which will inevitably lead to confusion among producers. Furthermore, these certification schemes fail to consider adequate life-cycle analyses, ignoring upstream and transport-related emissions that must be addressed. Consequently, the EU must step in.

For Saudi Arabia and the Gulf countries at large, not only the threat of billions of dollars' worth of fossil fuel-based stranded assets plays a role in our argument for a balanced approach. The land-use and infrastructure challenges related to the necessary additional renewable energy are massive. This means there is considerable potential for the availability of this hydrogen to be delayed while suggesting that renewable energy-derived hydrogen should be supplemented by fossil fuel-based hydrogen options. This should include requirements for associated CCS, including a strict certification system for low-carbon gases according to a life-cycle assessment of GHG emissions (Azadegan et al. 2022). For example, Saudi Arabia's installed (and planned) renewables capacity is minimal. Is it realistic to assume that it can decarbonize its heavily carbon-intensive electricity grid with a 50% renewables target by 2030? This would need to be done while simultaneously ramping up the renewables capacity required to produce the hydrogen needed to meet Europe's towering import target. This is only realistic if the EU and Saudi Arabia agree on a joint development and import and export policy framework that incentivizes investment, enhances the bankability of projects, and much more.

Further, much of the world is suffering a gas-price crisis, which makes low-carbon hydrogen unattractive in the short term. However, Saudi Arabia neither imports nor exports natural gas, meaning the price is unaffected by global markets (Radowitz 2022). This allows energy giants such as Aramco to preserve its gas reserves for higher value-added products. Aramco is also targeting the annual production of up to 11 Mt of blue ammonia by 2030, which requires 1.93 Mt of low-carbon hydrogen produced from natural gas via CCS (Saudi Aramco 2022). Europe’s determined focus on renewables-based hydrogen will not deter players such as Aramco from abandoning these types of ambitions. On the contrary, it will merely further cement the strong economic ties between Saudi Arabia and other Gulf countries with willing off takers in Asia such as Japan and South Korea. As Asia’s requirements on the method of production are less strict than in Europe, this could undermine the EU’s capability to form mutually beneficial strategic partnerships based on a mutual understanding of common value creation, shared norms, and the acknowledgment of certification schemes.

Finally, Saudi Arabia is determined to become a powerhouse producer and exporter of hydrogen (and ammonia) by 2030. Indeed, it is aiming to export 4 million Mt, with 3-Mt low-carbon of hydrogen (and ammonia) and 1 Mt that is renewables-based (Saudi Green Initiative 2022). Moreover, while REPowerEU does not exclude low-carbon hydrogen, Gulf countries see renewable hydrogen development in conjunction with the low-carbon variant, at least until 2030. This difference in focus is part of a more significant schism. Whereas Europe is focused on eliminating carbon emissions in the medium-to-long term, Saudi Arabia’s CCE approach focuses on commodifying carbon emissions. The country is attempting to move the discourse on CO_2 away from being viewed solely as a negative externality and toward the value that can be extracted from it.

The difficulty in reconciling these different visions was made clear during the Saudi presidency of the group of the world’s largest economies plus the EU, or ‘G20’ in 2020. In a last-minute effort of political logrolling, EU leaders endorsed the Kingdom’s CCE approach in exchange for a renewed commitment to phasing out fossil-fuel subsidies which the Saudi presidency had attempted to remove from G20 documents (Farand 2020; Lo 2020). Preferably as part of the EU’s Strategic Partnership with the Gulf, the EU should recognize that for a subset of countries like Saudi Arabia, developing the capacity to reduce, reuse, recycle, and remove CO_2 makes sense. These countries are heavily dependent on oil exports, face huge challenges in diversifying their economies, and are facing growing pressure from major consumer blocks like the EU to reduce emissions. The recognition by Saudi Arabia that rechanneling the vast government support for fossil fuel production and consumption to clean energy alternatives would provide an opening for deliberation with the EU and its political agenda of leveling the playing field for truly affordable, clean energy services (Schröder, Bradley, and Lahn 2020).

To drive a coherent scale-up of clean hydrogen, Gulf producers require a policy framework that validates the necessary investment. Even beyond the mixed signals coming from Europe, the lack of on-the-ground engagement and absence of plans for low-carbon hydrogen offtake agreements from European actors make major Gulf energy players reluctant to invest in production projects (Azadegan et al. 2022). Simultaneously, Saudi Arabia's hydrogen target of 4 Mt by 2030 is too low for it to become a world-leading exporter. The Kingdom must at least double its goal to 8 Mt of exports by 2030. In addition, the EU would be a more than willing partner under certain conditions. First, the Kingdom would have to be willing to offer 2 Mt of low-carbon hydrogen per year from 2028 for €1.5/kg and deliver this to Crete (Greece) by pipeline. It would also have to accept an equal share of the cost for transport and storage facilities.

To find a balanced policy approach in renewable and low-carbon hydrogen, the EU-initiated Strategic Partnership with the Gulf should aim to address the following:

- Set up a long-term strategic partnership with the Gulf countries based on a mutual understanding of value creation, norms, and certification schemes. The latter includes enacting a harmonized certification scheme for clean hydrogen in the EU that defines a life-cycle analysis that considers upstream and transport-related emissions (Lockwood and Bertels 2022).
- Provide the necessary funding and the security of guarantees for building the hydrogen backbone and the corridors into the EU, including intercontinental transport and storage facilities (e.g., across the Mediterranean).
- Use existing instruments to flesh out the EU's tool box such as H2Global. This will save time and avoid costly competition.
- While prioritizing renewable hydrogen and derivatives, the European Hydrogen Bank's mandate should support low-carbon hydrogen for both EU production and imports.
- Resolve barriers to a flexible and international market for CO_2.
- Offer know-how and support on the EU's Important Projects of Common European Interest approach. Explain how Saudi Arabia and other Gulf countries can benefit by participating in projects modeled on this approach, such as regional CCUS hubs and hydrogen valleys.
- Consider the cross-cutting role hydrogen plays in Saudi Arabia's CCE approach. Chapter 2 explains that hydrogen cuts across all four pillars (i.e., reduce, recycle, reuse, remove) of the CCE. The renewables-based variant reduces and recycles emissions (e.g., via synthetic fuels) and the low-carbon variant either reuses emissions (e.g., in enhanced oil recovery) or removes them via CCS (IEA 2020).

A concrete example relevant in the partnership with the Gulf is the emerging cooperation between the EU and Egypt on renewable hydrogen. Both parties signed a Memorandum of Understanding (MoU) on this issue during the Conference of the Parties (COP) 27 in Egypt in 2022 which marks the intend to work jointly on developing the production, consumption, and trade of renewable hydrogen and its derivatives (European Commission 2022d). The MoU aims to mark the start of an ambitious and long-term partnership aimed at supplying Europe with renewable hydrogen and supporting Egypt's pathway to low emissions and finding green energy alternatives via European technology transfer and innovation and industrial partnerships between Egyptian and European companies. In turn, environmental constraints are to be considered the MoU states that both parties will cooperate on adopting the sustainable use of desalinated water as well as on mutually compatible regulatory frameworks that facilitate 'compliance with necessary European standards, definitions, and rules applicable to qualify as renewable hydrogen' (European Commission 2022d). In sum, the EU's MoU with Egypt demonstrates an intend to work constructively with a fossil fuel-exporting country on a mutually beneficial hydrogen partnership. This approach could be replicated with the likes of Saudi Arabia.

If no constructive modus operandi can be found, the longer the EU takes to present its vision for clean hydrogen imports, the longer it will take for the continent and Gulf region to transition away from the status quo. This would mean the continued extraction, transport, and consumption of unabated fossil fuels. This would strengthen the Gulf region's ties with Asia and result in progress on the Paris goals drifting further out of sight (Tovar and Azadegan 2022).

Finally, only some EU and non-EU countries (e.g., Denmark, Germany, the Netherlands, and the United Kingdom) have national CCS policies for achieving their net-zero ambitions. Germany and the Netherlands are expected to develop into large-scale importers of hydrogen, whereas Portugal, Spain, and Italy are set to become exporters or transit hubs. Several hydrogen frontrunner countries have formulated strategies and targets for installed hydrogen production capacity by 2030 to support the EU's goals (Table 8.2).

TABLE 8.2 Key production targets for 2030 in various national hydrogen strategies and estimations

	Electrolyzer capacity (GW)
France	6.5
Germany	10
Italy	5
Portugal	2–2.5
Spain	4
The Netherlands	3–4/6–8**
Denmark	4–6
The United Kingdom (non-EU)	10
Scotland (non-EU)	5
Estimations:	
Hydrogen Europe*	***118***
Aurora Energy Research**	***142***
REPowerEU**	***192***

Source: Beer (2022); Hydrogen Europe (2021); Van Wijk, Westphal, and Braun (2022).

Notes: Total planned capacity of power-to-hydrogen projects across Europe *before and **after the outbreak of the war in Ukraine.

At the end of 2022, twelve EU member states made electrolyzer capacity commitments for 2030 totaling almost 40 GW (Yovchev, Muse and Muron 2022). This is significantly below the number needed to reach REPowerEU's new target of 10 Mt of domestic renewable hydrogen production by that same year.

While governments generally recognize hydrogen as indispensable for reducing GHG emissions in Europe by 55% (compared with 1990) by 2030, national strategies differ depending on the country's interests and industrial strengths. Below, we discuss the approaches of some of the critical hydrogen actors in Europe.

France is focused on replacing carbon-based hydrogen in existing industrial sectors (e.g., refining, chemistry, and agribusiness). It also aims to pilot projects in the maritime and aviation industries and become a key producer of electrolyzers. France's focus on low-carbon electricity has opened the door to nuclear-powered hydrogen. French hydrogen production is the subject of a 'struggle' between utilities and transmission system operators. On the one hand is Électricité de France, the country's powerhouse utility. It appears to prefer a scenario in which local hydrogen production, part nuclear- and part renewables-driven, feeds electrolyzers near consumption points to decarbonize France's heavy industry. On the other hand, natural gas transmission system operators such as GRTgaz are collaborating with their German counterparts. This cooperation is focusing on cross-border hydrogen infrastructure projects that connect the Saar (Germany), Lorraine (France), and the Luxembourg border and enable the connection to the industry-initiated European Hydrogen Backbone (EHB; see Section 2.3). At the end of 2022, and in the wake of Europe scrambling to secure alternative energy supplies in the face of a squeeze from Russia, France agreed with Spain and Portugal on building Europe's first major green hydrogen corridor between Zamora (Spain) and Celorico (Portugal) and Barcelona and Marseille called 'H2med'. H2med will be able to transport 2 Mt of hydrogen in Europe by 2030 (H2med 2022). The announcement by France and Germany in early 2023 about the extension of H2med to the latter may indicate a possible reproachment between the French vision of a hydrogen future based on sovereignty and production within Europe and the German internationalist approach.

Germany is Europe's biggest hydrogen producer and consumer. It is also a premier proponent of international cooperation centered on imports and partnerships with exporting countries (Hydrogen Europe 2021). The German government has earmarked €9 billion to implement its national hydrogen strategy, namely, €7 billion domestically and €2 billion for international cooperation. It is also investing another €350 million ($405 million) to support renewable hydrogen-based projects overseas (Federal Ministry for Economic Affairs and Energy 2020). Germany has sought global partners to provide Europe's largest economy with vast amounts of green hydrogen from inexpensive renewable energy at the best locations worldwide while simultaneously promoting domestically manufactured electrolyzers and other hydrogen technologies 'made in Germany'. The federal government has identified a need for between 90 and 110 TWh_{HHV} (between 2.3 and 2.8 Mt per annum) of climate-neutral hydrogen by 2030, mainly for the steel and petrochemical industries. A large proportion of this will need to be covered by imports. Believing that the renewable energy supply can be ramped up fast enough to produce sufficient quantities of green hydrogen, the revised German national hydrogen strategy will mention blue hydrogen for a transition phase to meet demand, especially from industry, which offers a window of export opportunity for the Gulf countries (Collins 2022a).

With reference to the Gulf region, Germany is the only European country that has established a bilateral hydrogen partnership with Saudi Arabia (see Chapter 2). The German–Saudi MoU aims to promote bilateral cooperation in the production, processing, application, and transport of clean hydrogen (Federal Ministry for Economic Affairs and Energy, 2021). Germany is also in the process of establishing a comprehensive hydrogen value chain with the United Arab Emirates, which is Germany's largest trading partner in the Gulf region. At the end of 2022, the first-ever hydrogen-based ammonia test cargo arrived from the Abu Dhabi National Oil Company to the German copper producer Arubis. Further ammonia test cargoes are scheduled to arrive in Germany (Emirates News Agency 2022).

Italy's National Hydrogen Strategy Preliminary Guidelines are targeting the production of green hydrogen by introducing 5 GW of electrolyzer capacity and a 2% hydrogen penetration into final energy demand by 2030 and up to 20% by 2050 (IEA 2021). The Italian market's extensive renewable energy assets and country-wide gas transport network make it attractive for developing green hydrogen. This will allow the dissemination of power-to-gas technology based on the storage of surplus electricity produced by solar, wind, and hydraulic power plants in the form of methane and hydrogen. Unlike France's focus on industrial usage near consumption, Italy is pushing to blend hydrogen in the grid for use by medium-sized players. One opinion is that the country will become self-sufficient in meeting most of its demand. Moreover, given Italy's central location in the Mediterranean, it is ideally situated to become a hub for hydrogen trade, as it lies between potential major exporters in Africa and the Middle East and consumers in northern Europe (Mazzei 2021). For example, Snam, a major natural gas grid operator, has a stake in pipelines carrying Algerian gas into Italy, which is seen as paving the way for green hydrogen imports from Africa into Europe (Jewkes 2021).

Norway is delivering around a quarter of Europe's gas needs, primarily through pipelines (Offshore 2022). In the short term, it is emphasizing its role as a provider of low-carbon hydrogen. For example, it is producing hydrogen close to customers and transporting the CO_2 back to Norway to be stored in its vast storage capacities (World Energy Council 2021). The Norwegian hydrogen strategy could also aim to blend natural gas with hydrogen in the existing pipeline grid for export. The United Kingdom, Germany, and the Netherlands are major collaborators for blue hydrogen (via the CO_2 return option). Equinor, the Norwegian energy company, is studying the possibility of delivering natural gas to Germany and the Netherlands to be converted into blue hydrogen. The hydrogen would then be transported to a steel plant in Duisburg, Germany, and the CO_2 would be shipped back for storage under the seabed of the Norwegian shelf of the North Sea.

Portugal is focusing on producing and incorporating renewable gases, including green hydrogen, mainly in sectors where electrification is not cost-effective. It is also focusing on decarbonizing parts of the national economy, such as industrial processes in chemicals, cement, and the production of raw materials. By 2030, hydrogen should reach 5% of the country's final energy consumption. In addition, the Portuguese government is considering the export of renewable hydrogen to the EU (World Energy Council 2021). Its potential to produce cheap hydrogen is enormous because of its access to excellent offshore wind; moreover, it secured the world's lowest winning solar bid in 2020 (Bellini 2020a). In this context, the Portuguese and Dutch governments are working on connecting the 1-GW green hydrogen project on the industrial site of Sines to the Port of Rotterdam. Another project is to develop a strategic export–import value chain to produce and transport hydrogen to the Netherlands (Bellini 2020b).

Spain is focusing on the production and domestic consumption of renewable hydrogen. Next to an installed electrolytic hydrogen production capacity of at least 4 GW, Spain aims to run large commercial hydrogen-based energy storage projects. The government is striving for 25% of renewable hydrogen within the industrial hydrogen mix by 2030. The country's gas grid operator, Enagas SA, is one of 23 transmission system operators proposing a Europe-wide hydrogen network, or the "European Hydrogen Backbone" (EHB). The EHB intends to create a 22,900-km grid by 2040 (see the fifth section). The country is also home to HyDeal España, whose production is scheduled to begin in 2025. Its total installed capacity is expected to reach 9.5 GW of solar power and 7.4 GW of electrolysis capacity by 2030. The International Renewable Energy Agency (IRENA) ranked 'HyDeal' as the largest GW-scale renewable hydrogen project globally (IRENA 2022). Roughly 10 GW of renewable hydrogen will be produced in Spain by 2030 if all announced projects proceed as planned, which is a 150% higher than the current 4 GW target (Collins 2023a).

The Netherlands is Europe's second-largest producer and consumer of hydrogen after Germany and is home to the continent's largest port, namely, the Port of Rotterdam. Following REPowerEU, the Port of Rotterdam strengthened its aim to become Europe's premier hydrogen hub by announcing that it will supply northwestern Europe with 4.6 Mt of hydrogen annually by 2030 (Port of Rotterdam 2020). At the Port of Eemshaven in the north of the Netherlands, a 10-GW hydrogen hub is planned to generate 3–4 GW of wind energy for producing hydrogen before 2030, possibly rising to 10 GW around 2040. The country has also started work on a national hydrogen backbone, which could be ready by 2027 following the initial construction of hydrogen infrastructure from 2024 in the Rotterdam region (Stones 2022). Different from the overall EU focus on renewable hydrogen, in the

Dutch–Saudi MoU on Energy from 2023, the two kingdoms aim to encourage bilateral cooperation on 'clean hydrogen' and carbon management (i.e., capture, utilization, transport, and storage) via regular high-level, government-to-government consultations, and mutual support for net-zero policies in frameworks like the CCE (Rijksoverheid 2023). The Dutch–Saudi MoU points toward encouraging a more pragmatic and 'balanced' partnership on clean carbon hydrogen similar to that proposed in this chapter.

Despite these developments, we argue that there is a very serious risk that the EU will not be able to achieve its ambitious hydrogen objectives due to slow implementation, fragmentation, and lack of strategic alignment between key member states. The consequence of an inability to formulate a coherent hydrogen strategy for Europe may well be severe deindustrialization (van Hulst and Westphal 2023).

Table 8.3 describes several barriers related to demand, costs, infrastructure and standards, and certification as well as enabling measures that must be implemented over the coming decade (IRENA and World Economic Forum 2021).

The national hydrogen pathways in Europe are generally marked by:

i A gap between ambition and policy.
ii Discord between import- and export-oriented countries.
iii An incoherent assortment of hydrogen colors and carbon intensity.
iv A lack of proper infrastructure planning.

Regarding **point (i)**, there is considerable skepticism about whether the EU and nation states can meet their decarbonization targets on time (Botts 2022). This is because it could take at least two years before final versions are hammered out at

TABLE 8.3 Barriers to and objectives of hydrogen development in Europe

Barriers	*Key objectives*
Production	Remove cost and regulatory barriers for production and deploy mechanisms to accelerate demand.
Demand	Drive critical mass demand through major hydrogen projects, leveraging efficient capital, long-term certainty, and sectoral and geographical targets.
Infrastructure	Ensure early ramp-up of 'no regret' infrastructure, including transport, storage, conversion, and trade facilities.
Pace of development	Accelerate the scale-up of electrolyzer manufacturing to drive economics of scale.
Standards and certification	Ensure clarity on carbon intensity, safety, and technical standards for projects across the value chain.

Source: IRENA and World Economic Forum (2021).

the EU level and subsequently implemented by its member states into national law. This leaves little time to phase out natural gas. Hence, the EU will need to work quickly and decisively to decarbonize the gas sector, with reductions in fossil gas consumption of 32%–37% required by 2030, in line with its impact assessment (European Commission 2020b).

A pragmatic approach provides tailored support to selected flagship projects such as industrial clusters in port areas in northwestern Europe's 'hydrogen advanced' area. These areas combine high volumes of existing fossil fuel-based hydrogen production that need to be decarbonized with logistical operations. Moreover, as these industrial clusters typically have a natural gas infrastructure, repurposing gas pipelines constitutes a low-cost option to build a hydrogen infrastructure (van Hulst 2021). Tailored support can be provided to selected flagship projects and scale up hydrogen value chains through two main initiatives. The first is the EU's Important Projects of Common European Interest, which provide state aid to address market failures for large cross-border integrated projects. The second is the EU-supported stakeholder forum, named the European Clean Hydrogen Alliance.

Set up by the European Commission in 2020, the European Clean Hydrogen Alliance brings together over 1,500 stakeholders from clean hydrogen production and transmission to industry, mobility, energy, and buildings applications. The Alliance has more than 750 projects in the pipeline for rolling out clean hydrogen on a large scale. Under this Alliance, and in the context of the EU's REPowerEU efforts, the Electrolyser Partnership was launched at the end of 2022. This Partnership brings together electrolyzer manufacturers and suppliers of components and materials. With support of the European Commission in removing regulatory, financial, and supply-chain roadblocks, the Partnership aims at achieving 17.5 GW of combined annual electrolyzer manufacturing capacity by 2025 (Azzimonti et al. 2022).

This time-saving flagship project approach is already common in Japan and Korea, but less so in Europe, where legislative and regulatory procedures can be long and cumbersome (van Hulst 2021). The European Commission urges member states to ensure the fastest planning and permitting procedures available when formulating renewable energy projects (European Commission 2022e). However, since energy policy is a predominantly national prerogative in the EU, national governments' willingness and ability to accelerate planning and permitting are ultimately decisive. For example, the German government intends to rapidly increase the number of onshore wind auctions and streamline permitting procedures for onshore wind. The target is to roughly double the capacity of onshore wind in the country to 115 GW by 2030, meaning annual capacity additions will have to reach around 10 GW as of 2025 (Appunn 2022).

While this wind power is required for the government's pledge that 80% of electricity will come from renewable sources by 2030, the necessary dedicated capacity for domestic hydrogen production is apparent. For Europe at large, the projected hydrogen demand of 2,150 TWh_{HHV} in 2050 would require around 2,530 TWh of dedicated renewable electricity. However, producing such quantities is subject to public acceptance of an accelerated renewable installed capacity expansion even beyond the planned expansion (Appunn 2022).

Europe's national hydrogen pathways are further characterized by discord (**point ii**) between countries and stakeholders. On the one hand are those nations with a strict focus on domestic production and demand (e.g., France). On the other are those with an export focus (e.g., Spain) or an international and import-oriented vision e.g., the Netherlands and Germany (Collins 2022b; Radowitz 2021). We argue that Europe will require vast amounts of imported hydrogen, primarily via pipelines. Besides the established technology, available infrastructure, existing ammonia market, and ongoing R&D, other factors will also have a defining role. In Germany, for example, limited space, high electricity prices, and demand challenge the continuous and competitive production of green hydrogen. Simultaneously, energy security issues, unstable political factors in exporting countries, and supply chain disruption risks provide incentives to retain a significant proportion of hydrogen production in Europe (Wietfeld et al. 2021). Therefore, pan-European initiatives such as the EHB (see below) and production projects between countries such as Spain, Italy, and Germany are being implemented or proposed (E.ON. 2021).

The discord between 'exporters' and 'importers' hinders the formation of a consistent and realistic external EU 'chorus' on hydrogen. This results in confusion among prospective exporters such as those in the Gulf, which assume that Europe's strategic priorities and demand preferences are focused exclusively on renewable hydrogen.[3] We argue that this discord should be replaced by a coordinated European import strategy that balances renewables and low-carbon hydrogen based on a grounded assessment of European production and demand capacities. Introducing flagship projects in industrial clusters is a good starting point. A subsequent scale-up and interconnection of these clusters via a pan-European infrastructure could strengthen the creation of a liquid hydrogen market, supplemented by imports via pipeline and shipping from exporters beyond Europe.

The discord and confusion for outsiders are further fueled by the 'hydrogen color debate' in Europe (**point iii**). National hydrogen strategies across Europe cite divergent forms of hydrogen based on the color or carbon intensity of production (Table 8.4).

In sum, the political discourse in Europe tends to focus on the color of the hydrogen produced. This focus is stifling innovation, with oversimplification and color prejudice risking the premature exclusion of technological routes that could be more cost- and carbon-effective (World Energy Council 2021). For the sake of consistency, transparency, and technological neutrality, European countries ought to understand the carbon intensity of hydrogen and adopt the EU taxonomy thresholds as reference points (Zabanova and Westphal 2021). These thresholds open the debate about the competition between various hydrogen production routes that meet the required carbon intensity at negligible costs. This will vary with the context, meaning that hydrogen produced using renewable electricity could be the most appropriate in one case. In another context, hydrogen produced with carbon capture could be more suitable and economical (World Energy Council 2021).

TABLE 8.4 Carbon intensity of hydrogen and summary of colors across Europe

Country	*By 2030*	*By 2050*	*Definition*
EU	Low carbon	Clean/ renewable	Natural gas + CCS* or using renewable power with the EU Taxonomy providing a benchmark of 3 tons of CO_2e per ton of hydrogen
France	Low carbon and fossil fuel-based	Low carbon	Low carbon: Electrolytic hydrogen production can include both renewable and nuclear power
Germany	Carbon-free	Renewable	Carbon-free: natural gas with CCS*, methane pyrolysis, etc. Renewable: using renewable power
Italy	Renewable and fossil fuel-based	–	
Netherlands	Blue and green	Green	Green: primarily electrolysis using sustainable electricity and biogenic feedstocks produced sustainably. Blue: produced from natural gas with CCS*
Norway	Clean	Clean	Clean: steam reforming of NG/other fossil fuels + CCS (90%–95% capture rate)
Portugal	Green	Green	Using renewable power
Spain	Renewable	Renewable	Water electrolysis using renewable electricity and hydrogen obtained by reforming biogas or biochemically converting biomass provided that the established sustainability requirements are met
United Kingdom	Low carbon (blue and green)	Low carbon (blue and green)	Natural gas + CCUS*, renewable electrolysis, nuclear electrolysis, bioenergy with CCS, thermochemical water splitting

Source: Authors adopted from the World Energy Council (2021); UK Secretary of State for Business, Energy & Industrial Strategy (2021).

Notes: *The carbon capture rate is not defined in the strategy.

Regarding **point (iv)** on infrastructure development, significant investment must be diverted into the hydrogen refueling infrastructure. This will be challenging, as almost 70% of all stations are located in Germany, which is planning for 1,000 stations by 2030 (European Commission 2021i).

Most member states are not planning for sufficient investment in the hydrogen refueling infrastructure to develop a coherent network across the EU (European Commission 2021i). Second, there is a lack of planning with regard to placing hydrogen assets where needed or making hydrogen deployment an integral part of the gas network while supporting electricity grid resilience and reliability. Instead, there is too much 'silo thinking' from the perspective of the needs of individual sectors. Experts therefore argue for proper planning of demand and linking gas and electricity networks accordingly.[4]

Application

The application of hydrogen is generally seen in Europe as a choice supplementary to large-scale electrification and increased energy efficiency. Nonetheless, it is essential for the comprehensive decarbonization of the EU's economic sectors, as shown in Figure 8.9.

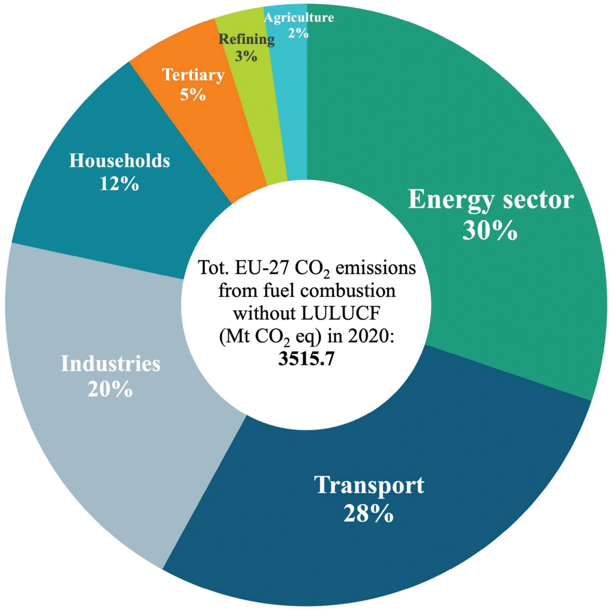


FIGURE 8.9 EU CO_2 emissions from fuel combustion by sector (Kt. CO_2 eq.), excluding land use, land-use change, and forest (2020).

Source: Jan Frederik Braun based on Enerdata (2022).

Regarding energy supply, the EU's energy transition requires almost completely decarbonized power generation, which implies the need to integrate renewables into the grid. Hydrogen is the only at-scale technology for 'sector coupling', which allows for converting generated power into a usable form, storing it, and channeling it to end-use sectors to meet demand. The advantage of hydrogen over other flexible power options such as batteries and demand response is that it can be supplied and stored in large quantities at relatively low investment. This makes it particularly appealing for long-term storage (Guidehouse 2021a). Furthermore, hydrogen plays a significant role in the decarbonization of gas supply. The latter connects Europe's industry and delivers more than 40% of heating in EU households and 15% of EU power generation (Fuel Cells and Hydrogen 2 Joint Undertaking 2019). Other options are seen as insufficient due to a lack of the necessary scale (i.e., biogas) or costly. Some are even impossible, as in electrification with heat pumps, which requires old buildings to be retrofitted (Fuel Cells and Hydrogen 2 Joint Undertaking 2019).

In the domestic and international transport sectors, hydrogen is a promising decarbonization option and fuel. Here, electrification has significant disadvantages due to the low energy density (i.e., lower range), high initial costs, and slow-recharging performance of batteries. Transport modes targeted in Europe include heavy-duty trucking. Meanwhile, hydrogen and synthetic fuels based on hydrogen are seen as the only at-scale option for direct decarbonization of the aviation and maritime shipping sectors. In addition, the hydrogen refueling infrastructure has significant advantages over fast charging in terms of the required space in urban areas and highways and reduced requirement for considerable electricity grid upgrades.

To decarbonize industry, hydrogen is seen as an essential feedstock when electrification is not an option. This is particularly so for ammonia, methanol, high-value chemicals, iron and steel, and bio and synthetic kerosene production (Guidehouse 2021a). The most significant share of hydrogen demand in Europe comes from refineries, followed by the ammonia industry. These two sectors consume four-fifths of hydrogen consumption in the EU and the United Kingdom (Hydrogen Europe 2021). Thermal production methods (e.g., reforming, partial oxidation, by-production from refining operations, and by-product production from ethylene and styrene) dominate total capacity in Europe, whereas electricity-based hydrogen (power-to-hydrogen, PtH) constitutes only a minimal share.

Overall, transport and industry are the most prominent application sectors in Europe. Industry has a particularly prominent role in countries with a robust industrial presence and high priority on reducing GHG emissions, such as Germany, France, the Netherlands, and Spain (Figure 8.10).

All these countries mention the possibility of using hydrogen in the industry sector, although often without concrete steps, actions, or targets. Their focus is typically on existing chemical processes such as ammonia and methanol production. In addition, clean hydrogen use in refineries will play a critical role in Germany,

Hydrogen use sectors	EU	DE	FR	IT	NO	PO	ES	NL	UK
Industry	✓	✓	✓	(✓)	✓	✓	✓	✓	✓
Power	(✓)	(✓)	✓	✗	✗	(✓)	(✓)	(✓)	✓
Transport	✓	✓	✓	(✓)	✓	✓	✓	(✓)	✓
Buildings	(✓)	(✓)	(✓)	✗	✗	✗	✗	(✓)	✓
Export	✗	✗	✗	✗	✗ 2)	✓	✓	✗ 1)	✗

✓ main sector (✓) less relevant ✗ not addressed

1) Hydrogen imports transit to other countries (e.g. Germany) considered.
2) For Norway, hydrogen is not targeted for direct export, but indirectly through the export of NG with local CCS.

FIGURE 8.10 Main target sectors of current hydrogen strategies per country.

Source: Jan Frederik Braun and Yunus Syed adapted from World Energy Council Germany (2020).

the United Kingdom, and France due to the regulations included in the EU’s RED. Steelmaking is recognized by a few strategies, including in the EU, Germany, the United Kingdom, and France. However, this is mainly considered in the long term, as the sector’s transition to an entirely new technology will take time (World Energy Council Germany 2020).

Where the building sector is targeted, such as in the United Kingdom, the distribution and transmission of hydrogen within gas networks and converting buildings and appliances using hydrogen are central strategic elements. Overall, the general approach in Europe is to increase the share of low-carbon gas, improve building insulation, and implement intelligent hybrid solutions. These solutions include insulating, which is easy and cost-effective, using a heat pump for baseload heat, and supplying the peak demand and hot water with a hydrogen boiler.

European research and innovation in hydrogen technologies

The most common commitment in EU member states’ strategies are electrolyzer capacity and public funding for hydrogen technologies (Yovchev, Muse and Muron 2022). Regarding European hydrogen production, capacity was spread over more than 500 production points in 2019, which totaled 10.5 Mt of hydrogen per year. However, it was dominated by ‘thermal’ production methods such as reforming, partial oxidation, by-product production from refining operations, and by-product production from ethylene and styrene (Figure 8.11).

To quickly improve on these meager numbers, the continent is leading electrolyzer capacity deployment, with 40% of global announced capacity (Hydrogen Council 2023). Europe, which has traditionally held a strong position in electrolyzer manufacturing, is thus set to remain the largest market in the near term. Even

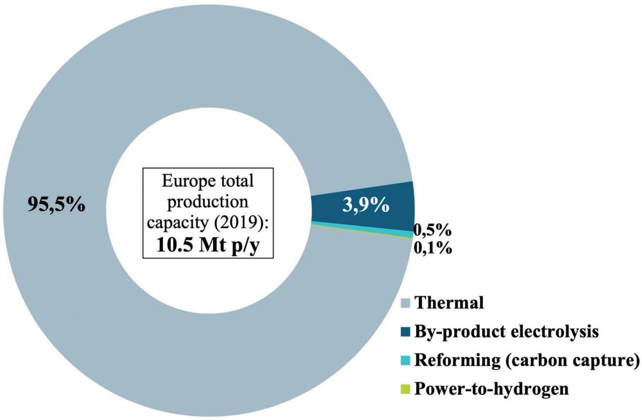


FIGURE 8.11 European hydrogen production capacity by technology in 2019.

Source: Jan Frederik Braun based on Hydrogen Europe (2021). The 10.5 Mt number excludes by-product hydrogen generated as part of coke over gas.

today, roughly half of all electrolyzer manufacturers are located in Europe and component suppliers are primarily European (Fraunhofer ISE 2020). And while Europe is the largest global market regarding announced electrolysis capacity, only a fraction of this capacity has passed final investment decision, e.g., less than 2% in 2023 (Hydrogen Europe 2023).

The EU is geared explicitly toward maintaining the region's competitive strengths in electrolyzer manufacturing. Its Hydrogen Strategy states that the EU's preference for renewable hydrogen builds on European industrial strength in electrolyzer production. Europe is highly competitive in manufacturing clean hydrogen technologies and well positioned to benefit from the global development of clean hydrogen as an energy carrier (European Commission 2020a). Europe has a strong desire to prevent its fledgling hydrogen industry from following the path of the continent's solar power-to-hydrogen (PV) industry. While the hydrogen industry once held a solid position in Europe, particularly Germany, this collapsed in the face of cheaper Chinese solar modules (IRENA 2022). However, the electrolyzer industry has multiple issues with the EU's hydrogen approach. Electrolyzer manufacturers have front loaded massive investment to reach their current capacities and need clear signals to invest more (e.g., clear demand-side targets for green hydrogen).[5]

CCUS has been acknowledged in the context of the European Energy Union as a fundamental research and development priority to achieve the 2050 climate objectives in a cost-effective way. Overall, the EU is in a good position when it comes to publications, patents, and private and public R&I (Kapetaki et al. 2022). Also, a sufficiently high carbon price under the EU ETS may promote business and technology developments in CCUS across the continent. On a national level, France, Germany, and the Netherlands are the front runners in public and private R&I investments and top patenting companies. On the downside, Europe is lagging the US in terms of early-stage venture capital investments (ibid.). Areas for research that are recognized by the European Commission’s Joint Research Center (JRC) include improving solvents’ performance and environmental friendliness for CO_2 capture (ibid.). The JRC also mentions increasing the efficiency of CO_2 utilization pathways, which will require intensified research on improved catalysts, higher efficiency levels, lowering costs, and new routes to carbon-based functional materials. Concerning CO_2 storage, and again according to the JRC, research priorities should be focused on increasing capacity, understanding large scale and optimizing injection and demonstrating reliable monitoring techniques (ibid.).

A hydrogen project consortium can apply to several EU funding programs, such as the public/private Clean Hydrogen Joint Undertaking, which accelerates the development and improvement of clean hydrogen applications (Clean Hydrogen Partnership n.d.). This is a public/private partnership between the European Commission, fuel cell and hydrogen industries (represented by Hydrogen Europe), and the research community represented by Hydrogen Europe Research. Combined, it aligns European research and industry to a common agenda (Figure 8.12).

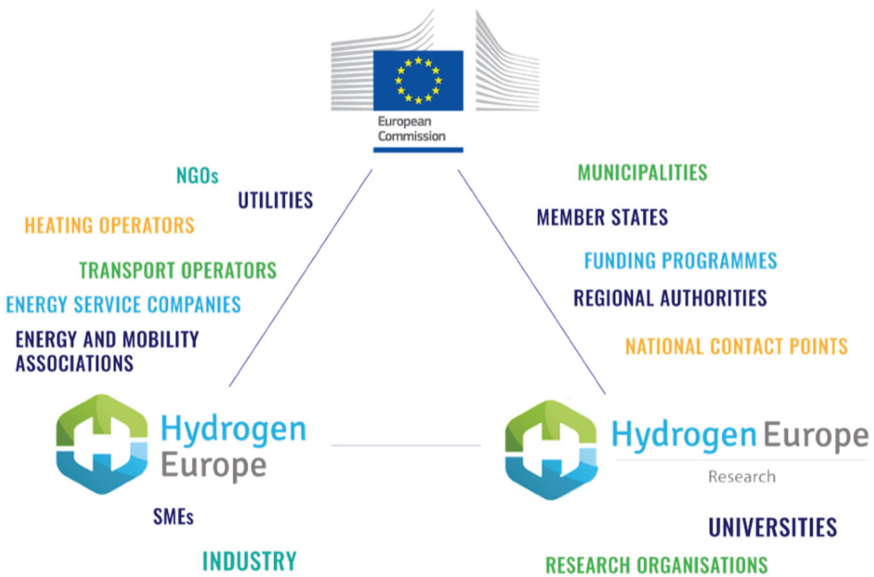


FIGURE 8.12 Clean Hydrogen Joint Undertaking.

Source: Green Hysland (2022).

Over the last decade, the EU contributed around €900 million ($1 billion) to support R&I activities in hydrogen technologies in Europe. In particular, the Fuel Cells and Hydrogen Joint Undertaking has funded 285 research and demonstration projects with a budget of around €1 billion ($1.2 billion; FCH 2020). These efforts have enabled several technologies to mature, such as buses, passenger cars, vans, material-handling vehicles, and refueling stations.

Building on the work of the Fuel Cells and Hydrogen Joint Undertaking, the Clean Hydrogen Partnership will accelerate the development and deployment of a European value chain for clean hydrogen technologies. It will focus on producing, distributing, and storing clean hydrogen and supplying sectors that are hard to decarbonize, such as heavy industries and heavy-duty transport applications (European Commission 2021j).

Some EU research objectives could be challenging to meet. For example, increased focus on innovation and R&D is necessary to enable technology scale-up regarding the following (IRENA and World Economic Forum 2021):

- Mass producing cells and stacks to lower the cost.
- Implementing wind-to-hydrogen projects, which link wind turbines and PV arrays to electrolyzer stacks directly at the DC electricity level and subsequently pass the generated electricity through water to split it into hydrogen and oxygen. These should be less expensive than a wind electricity turbine because of the less amount of electrical conversion equipment, which is replaced with an electrolyzer without adding extra cost.
- Ensuring the improved technology performance of electrolyzers and fuel cells, including durability, cost, and efficiency (and less critical material use).
- Scaling and sharing pilot projects to build experience with commercial-size facilities.
- Identifying possible long-term supply chain bottlenecks by value chain component.

Since hydrogen is a conversion rather than an extraction business, Germany is cooperating with export-oriented countries such as Saudi Arabia to develop hydrogen technology. As part of their MoU on hydrogen cooperation and as a leader in required technologies, Germany is supporting the entire value chain to speed the development of the R&D infrastructure in Saudi Arabia. Annex 2 discusses the potential areas of collaboration, which should be expanded to the EU level. It also describes some of the bilateral partnerships between European states and the Kingdom.

Case study: the European Hydrogen Backbone and Saudi Arabia

REPowerEU's target to import 10 Mt of renewable hydrogen rests on various volumes and transport modes. Table 8.5 presents one example of the volumes and transport modes required under the EU Hydrogen Accelerator initiative.

TABLE 8.5 Feasible EU options for importing 10-Mt hydrogen per year by 2030

Import type	*Volume (Mt/year)*	*Transport mode*	*Possible source countries/regions*
Ammonia	2–3 hydrogen (= 11–17 ammonia)	Ship	Chile, Namibia, Oman, Saudi Arabia
Hydrogen	4–6	New pipeline connecting Saudi Arabia, Egypt, Cyprus, Greece, and Italy Repurposed pipeline connecting Algeria, Tunisia, and Italy New or repurposed pipeline connecting Morocco and Spain	Middle East and North Africa: Morocco, Algeria, Tunisia, Libya, Egypt, Saudi Arabia
Hydrogen	2–3	New or repurposed pipeline connecting Norway, the North Sea, and Germany New or repurposed pipeline connecting the United Kingdom, the North Sea, and the Netherlands New or repurposed pipeline connecting the United Kingdom and Belgium	North Sea, Norway, the United Kingdom
Total	8–12 Mt 315–473 TWh_{HHV}		

Source: Van Wijk, Westphal, and Braun (2022).

We argue that the import goal of 10 Mt of hydrogen creates sufficient volume for a feasible business case for pipeline transport. A 48-inch hydrogen pipeline operating at 80 bar has a transport capacity of 15–20 GW hydrogen higher heating value (HHV) and can transport between 1.5 and 2.5 Mt per year (depending on full load hours). This cost-effective transport option can be considered in combination with shipping.

There is a rationale to import hydrogen and hydrogen derivatives by ship. The motivation for this import option is to create secure and flexible supply by diversifying imports from different regions. In addition, shipping has an advantage over pipelines across large and deep-water bodies and can also circumvent the crossing of politically unstable regions. Further, shipping routes can be modified to react to changes in market dynamics.

To facilitate the import of 10 Mt of hydrogen, REPowerEU mentions the development of three major hydrogen import corridors: via the North Sea, Ukraine (when possible), and the Mediterranean. In response to the REPowerEU ambitions, the industry-initiated EHB presented an accelerated plan involving 31 energy infrastructure companies from 28 countries. The EHB was first established in 2020 to develop a vision of a dedicated hydrogen pipeline transport network. The EHB argues that a dedicated European hydrogen infrastructure by 2040 requires an estimated investment of €27–64 billion based on using 75% of converted natural gas pipelines connected by 25% new pipeline stretches. The EHB states that repurposing existing natural gas pipelines to transport hydrogen is the most cost-effective solution for transportation up to 5000 km (Guidehouse 2020, 2021b). Figure 8.13

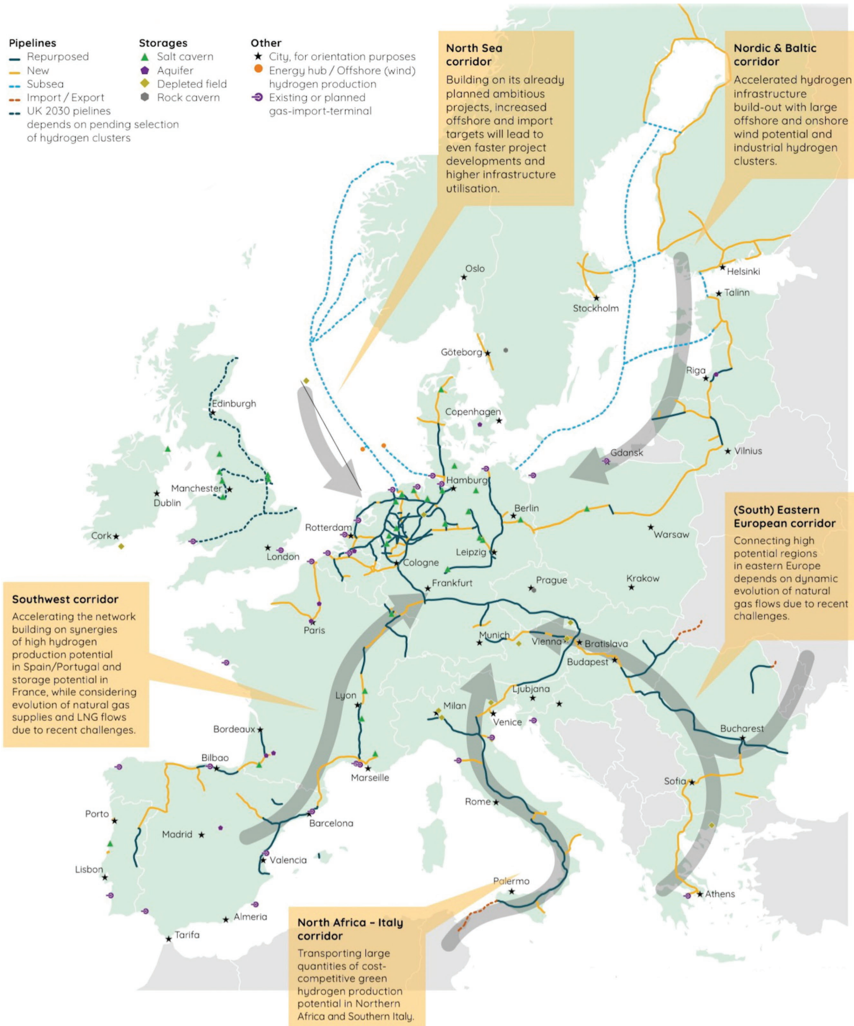


FIGURE 8.13 Accelerated 2030 EHB network that supports the REPowerEU ambitions.

Source: Guidehouse (2022).

shows the updated EHB plan supporting REPowerEU in up to five pan-European import corridors for large-scale hydrogen transport.

The Kingdom's clean hydrogen ambitions, based on low electricity prices and high load factors, are a strong fit for the EU's carbon-constrained hydrogen demand market. A recent estimation states that green ammonia from Saudi Arabia to Europe based on an electricity price of €1.5 ct/kWh ($1.7 ct/kWh) matches the fossil fuel-based local ammonia production cost. CO_2 prices would be around €60/tonne ($68/tonne), a price already reached under the EU ETS (Wietfeld et al. 2021). Based on this estimation, the cost of importing green hydrogen via ammonia for an exemplary industrial customer in Hamburg in 2025, including reconversion and distribution, could be around €4.10/kg ($4.60/kg) for Saudi Arabia. This is approximately €1.10/kg ($1.23/kg) cheaper than the hydrogen produced in Germany (Figure 8.14).

Next to shipping, the Saudi Energy Minister, His Royal Highness (HRH) Prince Abdulaziz bin Salman Al Saud, mentioned in early 2021 the idea of connecting Saudi Arabia to Europe via a hydrogen pipeline (IEF 2021). There are no concrete plans for turning this idea into practice for now. However, a linkage to the EHB-initiated east and southeast European corridor could connect Saudi Arabia with the European gas grid in a cost-effective manner. That is, transporting by pipeline is still significantly more cost-effective than any shipping option (Figure 8.15).

To illustrate a real-world comparison between pipeline and shipping, the EHB examines both options from Saudi Arabia to southeast Europe (i.e., via Turkey, Bulgaria, the Balkan countries, Slovenia, and Italy; Figure 8.16).

The EHB selected NEOM as the representative production site and Milan as the representative demand site. A pipeline from NEOM to Milan (3,500 km) was compared with a shipping route, including a pipeline from NEOM to Duba (300 km), shipping from Duba to Sicily (2,300 km), and a pipeline from Sicily to Milan

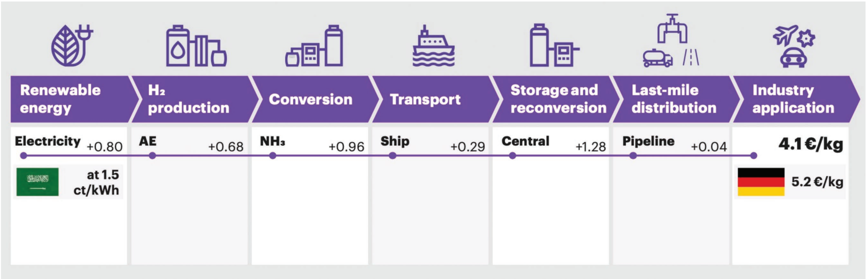


FIGURE 8.14 Modeling the cost of importing green hydrogen via ammonia from Saudi Arabia to Germany by 2025 (Euros per kg of hydrogen).

Source: Wietfeld et al. (2021).

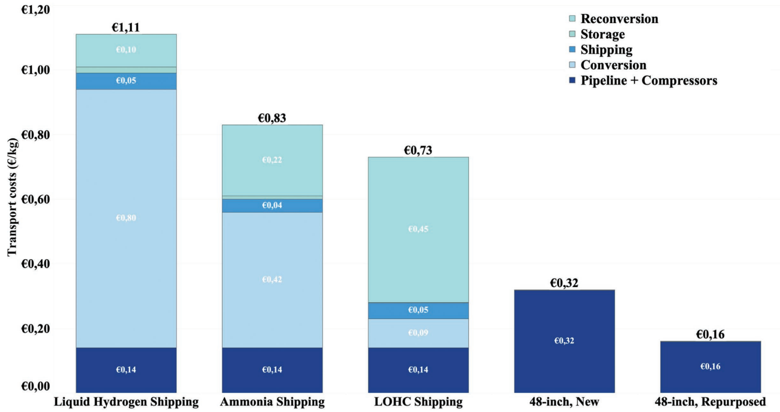


FIGURE 8.15 Comparison of the transport cost for Saudi Arabia to southeast Europe (Euros per kg).

Source: Jan Frederik Braun based on Guidehouse (2021a).

FIGURE 8.16 Comparison of shipping and pipelines as hydrogen transport methods from Saudi Arabia to southeast Europe.

Source: Authors adapted from Guidehouse (2021a).

(1,200 km). The dotted red lines from NEOM to Turkey and Greece indicate possible alternative routes under the Mediterranean Sea.

Shipping allows hydrogen exports to be started at lower volumes than pipelines, which are competitive only at large volumes and rely on high upfront investment. Saudi Arabia could thus focus on shipping hydrogen and hydrogen-based products to establish an initial value chain. NEOM, the new economic region development project along the Red Sea coast, is strategically positioned with excellent renewable energy resources and the accompanying capacity planning to kickstart these developments.

The pipeline route shown in Figure 8.16 is almost entirely land-based. The EHB analysis mentions that the routes and corresponding distances are illustrative and estimations. It is not stated that pipelines are prone to geopolitical risks. The pipeline route shown here from Saudi Arabia goes through a highly volatile country (Syria) and assumes a transit route via Turkey to Europe. Quickly changing geopolitical circumstances would make a hydrogen pipeline along this proposed route a high-risk/high-cost investment. Alternatively, it would be possible to build a shorter pipeline by routing part of it under the Mediterranean Sea. The Eastern Mediterranean basin is well known for its rich offshore salt caverns under the sea (Figure 8.17).

This is an ideal storage facility for the hydrogen produced in the Middle East and would also serve as a strategic hydrogen reserve for the EU (Chatzimarkakis 2022). This option could be attractive by combining the current development of the EastMed pipeline with low- and zero-carbon hydrogen production from natural gas (the latter via methane pyrolysis).

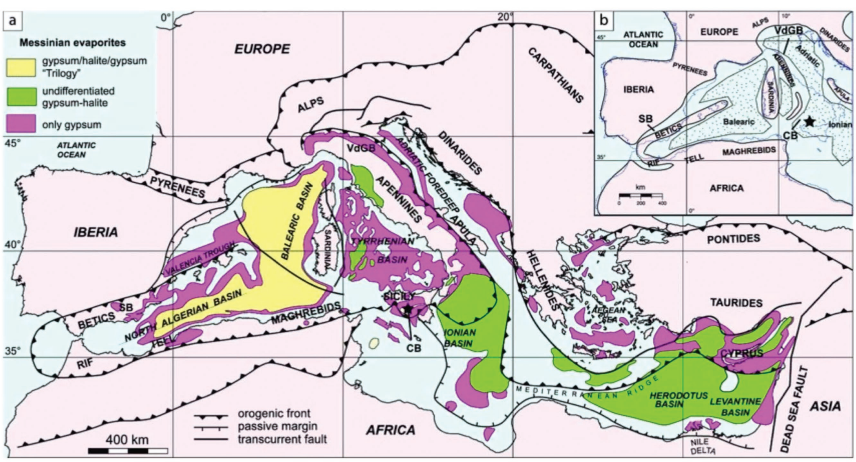


FIGURE 8.17 Hydrogen storage in offshore salt caverns under the Mediterranean Sea.

Source: Kuroda et al. (2014).

Note: Green areas are, in principle, suitable salt formations for salt caverns.

In the Eastern part of the Mediterranean Sea, natural gas has been found under the seabed areas of Egypt, Israel, Turkey, and Cyprus. Concessions for exploration have been granted. A gas pipeline under the Mediterranean Sea is foreseen to transport this gas to Europe by connecting Egypt, Israel, Cyprus, Crete, and Mainland Greece to Italy. This pipeline has a length of 1,900 km (1,300 km offshore and 600 km onshore), with two compressor stations in Cyprus and Crete. The pipeline capacity is in the first phase of 10 bcm (about 100 TWh), expanding to 20 bcm (about 200 TWh) in the second phase. It is estimated to become operational in 2025. However, it has been plagued by high costs, regulatory hurdles, and long-running tension between Cyprus, Greece, and Turkey over maritime borders and offshore oil and gas exploration. These issues forced the US government to withdraw its support from the pipeline, after which EastMed was declared 'dead' (Stamouli 2022).

As part of the EU's geopolitical awaking following the Russia–Ukraine war, we propose revitalizing the EastMed pipeline and designating and developing it as a clean hydrogen-ready pipeline. This would also have the advantage of complying with the aims and ambitions of the REPowerEU Hydrogen Accelerator. 'EastMedH_2' would allow a shift from natural gas to hydrogen. For this, hydrogen must be converted at the resource into low- or zero-carbon hydrogen using technologies such as auto thermal reforming with a CCS rate of 95%–98% (directly in the field) or methane pyrolysis, with only solid carbon as a by-product. These options could produce low- and zero-carbon hydrogen from natural gas at the resource. Saudi Arabia could then connect to EastMedH_2 via Egypt and supply Europe with either zero or low-carbon hydrogen. It could even become an active partner in developing this pipeline infrastructure by linking the dedicated hydrogen facilities in the NEOM region to the proposed southeastern European and Mediterranean corridors. This would include Sharm El-Sheik in Egypt, with links directly to Crete and mainland Greece as well as to Italy via the Poseidon interconnector pipeline, where it could join the EHB and provide the European continent with hydrogen. What speaks for our proposal is that EastMed H_2 could be linked via 'Poseidon' to the planned SoutH_2 corridor project (Figure 8.18).

If fully constructed, SoutH_2 would allow Europe to import four Mt of clean hydrogen per year from North Africa by 2030. The pipeline is planned to originate in the Hassi R'mel region in Algeria, which is Africa's largest natural gas-producing country and has a massive gas infrastructure. From here, the pipeline would run via the Tunisian town of Sfax across the Mediterranean Sea to Italy where it will continue through Austria and Germany. SoutH_2 is centered around the utilization of existing repurposed midstream infrastructure to transport hydrogen, with the inclusion of some new dedicated infrastructure where necessary. A high proportion of repurposed pipelines (>70%) will enable cost-effective transportation, whilst access to favorable renewable hydrogen

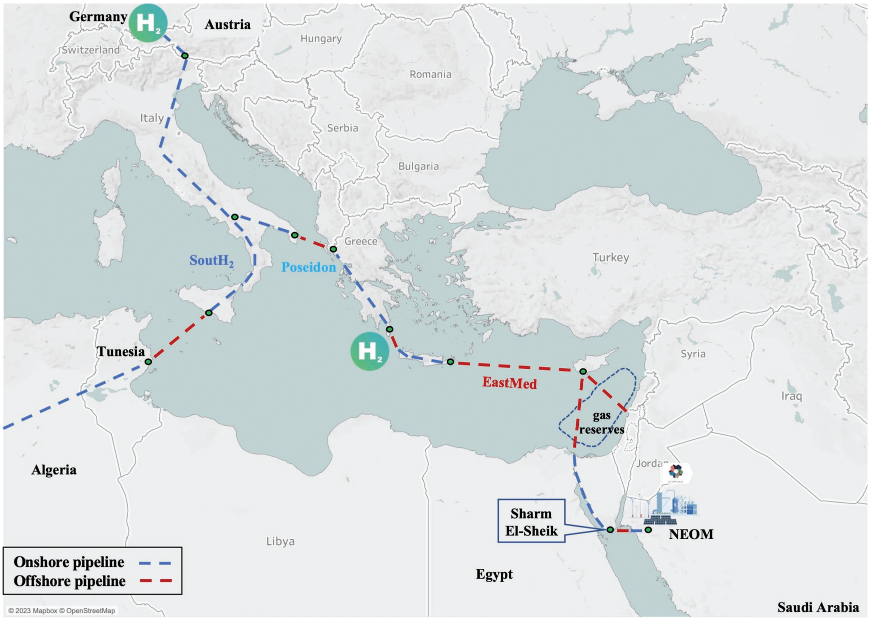


FIGURE 8.18 Proposed EastMedH_2 pipeline trajectory from Egypt and Saudi Arabia to Greece and Italy linked with the SouthH_2 pipeline through the Poseidon interconnector.

Source: Authors.

production locations (wind and solar) in North Africa would allow for switching from initially the transport of natural gas to low- and zero-carbon hydrogen from natural gas at the resource and green hydrogen. Second, SouthH_2 could deliver more than 40% of the REPowerEU import target (SouthH_2 n.d.). The four gas network operators in the SouthH_2 scheme—Italy's Snam, Germany's Bayernets, Trans Austria, and Gas Connect Austria—have all requested that the sections of the pipeline for which they will be responsible are allocated the status of an Important Project of Common European Interest by the European Commission—which will allow them to receive EU funding and accelerated permitting (Collins 2023b).

While it could be feasible for Saudi Arabia to connect to Egypt in this manner, the EastMedH_2 pipeline network would also include Israel in the project. While this geopolitical challenge must be solved for the sake of all regional stakeholders, we argue that it is worth the time and effort to do so. A combined 'SouthH_2/EastMedH_2' approach offers Saudi Arabia, Egypt, and other countries from North Africa and the Eastern part of the Mediterranean with the unique strategic opportunity to engage and commit a range of 'exporting' and 'importing' countries from different continents to an ‘important project of common Europe-MENA interest’. The EastMed H_2/SoutH_2 corridor constitutes an essential part of the EHB approach and could form a vital building block of a balanced European hydrogen partnership with Saudi Arabia and the Gulf.

Conclusion

Europe is the world’s leading hydrogen region owing to the comprehensiveness of its policy packages and combination of technology push, demand-pull, and fiscal policies. Only an energy system built around clean electricity and molecules can realistically achieve the EU’s intermediate target of a net 55% reduction in GHG emissions by 2030 and carbon neutrality by 2050. Hydrogen is essential to deliver cheap solar and wind energy cost-effectively at the right time and place and under the optimal transport and storage options. Ultimately, hydrogen will be applied in Europe to decarbonize hard-to-abate energy use. Overall, transport and industry are the most prominent application sectors in Europe. However, they are also seen as the only at-scale technology for sector coupling, which can convert generated power into a usable form, store it, and channel it to end-use sectors to meet demand.

Another driver is that Europe is highly competitive in manufacturing clean hydrogen technologies and well positioned to benefit from the global development of clean hydrogen as an energy carrier. The European hydrogen strategy is geared explicitly toward maintaining the region’s competitive strengths in these R&D fields and preventing its fledgling hydrogen industry from following the path of the continent’s solar PV industry. Europe leads in hydrogen production and storage technologies and traditionally held a strong position in the electrolyzer manufacturing industry. Even today, roughly half of all electrolyzer manufacturers are in Europe and their component suppliers are primarily European. Nevertheless, competition from countries such as China and the United States will increase in the coming years.

Regulatory approaches such as ‘Fit for 55 Parts I and II’ have initiated implementing the required regulations for an open and competitive clean and low-carbon hydrogen market in Europe to emerge. This is a pioneering effort, as internal markets for hydrogen and decarbonized gas globally do not exist. EU policymakers are committed to making Europe a carbon-constrained market in which unabated fossil fuels will play an increasingly marginalized role. This is also clear from EU efforts in constructing (international) hydrogen certification to ensure that a hydrogen is clean across the value chain.

Russia’s military attack on Ukraine in early 2022 has turbocharged hydrogen ambitions. The EU’s new energy strategy (REPowerEU) has doubled the initial target of the EU Hydrogen Strategy (i.e., 10 Mt of domestic renewable hydrogen production and 10 Mt of imports by 2030). The accompanying Strategic Partnership with the Gulf underlines the importance of cooperating with this region on renewable and low-carbon energy, including production, infrastructure, trade, and regulatory development. Saudi Arabia and other Gulf players are long-standing energy partners. However, they now have the capacity and know-how to produce low-carbon hydrogen and ammonia as well as the additional geopolitical and climate incentive to position themselves as reliable providers of clean energy imports for Europe.

However, while the EU recognizes the role of low-carbon hydrogen in reducing emissions of existing fuels in the short and medium term, its import focus is heavily biased toward renewable hydrogen. This is unrealistic. Europe is in a race to build renewables sufficiently fast to decarbonize the electricity grid. Hence, it may not have the additional renewable electricity needed to produce the volumes of renewable hydrogen required to meet the projected and massive increase in demand over the coming decades. From the perspective of major Gulf countries such as Saudi Arabia, this one-sided focus on green hydrogen is unrealistic for land-use and infrastructure challenges. Further, it lacks renewables capacity and results in less environmentally demanding competition from Asia. The production and infrastructure capacity required for green hydrogen needs to be scaled up at an incredible rate to meet Europe's towering import demands while simultaneously allowing for decarbonizing their own—extremely carbon-intensive—economies.

Second, several inconsistencies and discord mark national hydrogen pathways in Europe. There are gaps between the continent's strategic ambitions and the expeditious implementation of the required regulation and permitting. There is a lack of strategic alignment, or discord between hydrogen export- and import-oriented countries that could create confusion among exporters about Europe's strategic priorities and demand preferences. National political discourse also tends to focus on the color of hydrogen rather than the carbon footprints of hydrogen production methods. This represents a constraint and voluntary limitation compared with many other hydrogen-importing countries. This hinders the formation of a consistent and realistic external EU 'chorus' on hydrogen, creating confusion among prospective exporters in the Gulf region. This discord should be replaced by a coherent import approach that balances renewable and low-carbon hydrogen based on a grounded assessment of the production and demand capacities in Europe and the Gulf.

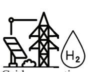
The EU Strategic Partnership with the Gulf and REPowerEU offer good starting points for this approach. The partnership can incorporate a policy framework for low-carbon hydrogen, including offtake agreements and support for an ambitious Saudi CCE program, which has a prominent role in clean hydrogen. REPowerEU's proposal of establishing hydrogen corridors, including one in the Mediterranean region, offers Saudi Arabia (and other Gulf states) a unique opportunity to develop a direct link with the planned EHB. The case study presented herein argues that Saudi Arabia is an excellent candidate to compare hydrogen transport options via pipeline and shipping. Based on the estimations of the EHB consortium, transportation by pipeline is significantly more cost-effective than all shipping options. However, the latter offers benefits in transporting hydrogen-based derivatives, providing market liquidity and supply security. In combination with the planned SoutH_2 corridor, revitalizing the EastMed pipeline and designating and developing it as a clean hydrogen-ready pipeline would allow Saudi Arabia to supply Europe with clean hydrogen. A combined SoutH_2/EastMedH_2 corridor will also create opportunities for the Kingdom to become an active partner in its development and engage it in further 'hydrogen-ready' infrastructure and storage initiatives that would align a range of 'exporting' and 'importing' states around a common 'EU-MENA purpose'.

Active engagement by exporters such as Saudi Arabia in initiatives such as these would provide considerable opportunities for its low-cost, renewable, and low- and zero-carbon hydrogen and hydrogen-based products. It would also offer a limited window of opportunity for the Kingdom and other Gulf exporters to push for parallel strategies for low-carbon and renewables-based hydrogen. This could foster local demand for hydrogen and facilitate financing for hydrogen and CCUS-related projects. It could also lead to investment in demonstration projects in pre-competitive technologies that have the potential to reduce the costs and improve the sustainability of hydrogen production. These engagements could effectively serve the purposes of decarbonizing the Gulf economies and their ability to move toward a more sustainable growth model that is less dependent on hydrocarbons and create a competitive advantage for them in Europe's carbon-constrained markets. In sum, these efforts would serve European and Gulf stakeholders in managing the transition to a global low-carbon economy.

Annex 1: The rules for producing renewable hydrogen in the EU (Stones 2023; European Commission 2023c, 2023d).

Pathways for producing renewable H_2

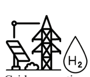
H_2 plant is directly connected to a renewable asset. The renewable asset cannot come into operation earlier than 36 months before the H_2 plant.



If the Proportion of renewable power exceeds 90% over the previous calendar year in the bidding zone where the hydrogen plant is operating.

H_2 takes place in a bidding zone where the emissions intensity of the grid is lower than 18gCO2e/MJ. However, the H_2 plant must acquire a renewable power purchase agreement (PPA), temporal and geographical correlation also apply.

Power supply can be considered renewable if taken from the grid duting an imbalance period. The power is either redispatched, or avoids redispatch.



A renewable PPA is signed for the suppyl of power, and the principles of additionality, temporal and geographical correlation apply.

Associated principles for production of renewable H_2

Principle	Conditions	Exemptions
Additionality	The renewable asset came into operation not earlier than 36 months before the H_2 plant & cannot have received operating or investment aid.	Principle does not apply until 1 January 2038 to H2 plants that come into operation begore January 2028.
Temporal correlation	<u>Up to 31 December 2029</u> H_2 prod. occurs within the same calendar month as the renewable power was generated under the renewable PPA. <u>Beyond January 1st 2030</u> H_2 prod. occurs within the same hour as the renewable power was generated under the renewable PPA.	Temporal correlation is considered as met if the H_2 prod. Occurs within the one-hour period when the clearing price for power resulting from the the day-ahead market is lower than or equal to €20/MWh, or lower than 0,36 times the EU ETS.
Geographical correlation	Considered if one of the following are fulfilled: • The renewable asset and H_2 plant are in the same bidding zone. • The renewable asset and H_2 plant are in interconnected bidding zones. The renewable asset is located in a bidding zone where the power price is equal to or higher than that of the H_2 plant. • The renewable asset is in an offshore bidding zone to the H_2 plant.	

Annex 2: Potential R&D areas for a Saudi–Germany hydrogen collaboration (Braun et al. 2022).

Hydrogen value chain	*Central themes*	*Potential R&D areas*
Production technologies	Green hydrogen	Efficiency improvement for solar PV and wind; improving capacity factors, digitization for variability and grid stability; system integration for hybrids, and decentralization.
		GW-scale alkaline water electrolysis; advancements in proton exchange membrane; solid oxide electrolyzer cell; anion exchange membrane; seawater electrolysis; materials for electrodes and separators; novel catalysts.
		Seawater reverse osmosis, renewable-driven water desalination.
		Brine treatment; membrane technologies.
	Blue hydrogen	Advance reforming technologies; auto thermal reforming; partial oxidation; reforming of liquefied petroleum gas; chemical looping; utilization of oxygen from electrolysis in reforming (combined blue and green).
		Gasification of petroleum residues and biomass; municipal waste; underground gasification; carbon-negative technologies.
		CCUS technologies (advanced solvents, cryogenic carbon capture); oxy-combustion; advanced thermodynamics cycles (e.g., Allam, supercritical CO_2 cycle); geological storage of CO_2; CO_2 leakage prevention.

(*Continued*)

Hydrogen value chain	*Central themes*	*Potential R&D areas*
		Direct air capture (DAC) technologies and services.
	Turquoise hydrogen	Natural gas pyrolysis; sour gas sweetening; solid carbon utilization.
	Other routes	Scaling up photochemical and microbial process-based hydrogen; microwave/plasma enabled the conversion of natural gas to hydrogen.
	Hydrogen valorization	Technologies for the reduced use of hydrogen in industry (e.g., hydrogen-less oxidative desulfurization of distillate and heavy fuels).
		Process improvements for hydrogen from refinery and industry by-products (e.g., Chlor-Alkali processes); waste heat recovery technologies.
Energy carriers; conversion, storage, transportation, and distribution	Physical conditioning	Gas separation and purification, e.g., pressure swing adsorption improvement and alternatives; efficient compression, liquefaction, and boil-off loss reduction in hydrogen transport; ultrasonics, cryogenics, and heat exchanger technologies; last-mile delivery loss prevention.
	Chemical conditioning	Ammonia alternatives to the Haber–Bosch process; electrochemical synthesis. Air-separation; ammonia cracking, catalysts; integration of renewables (e.g., solar-ammonia cracking); technologies for other carriers such as methanol, dimethyl ether, and formic acid.
		Metal hydrides.
		Liquid organic hydrogen carrier (LOHC).
		Battery for hybrids.
	Storage	Technologies for geological storage of hydrogen; saline aquifers, basaltic formations, ocean storage; round-trip efficiency.
	Transport	Trucks, pipelines; hydrogen embrittlement abatement: advance materials.
		Carbon-neutral shipping with fuel cells; ammonia, methanol, e-fuels.
Power (excess electricity) to X and sector coupling (electrification)	Chemicals and fuels	Synthetic or e-methane, ammonia, and methanol; process (e.g., Fischer–Tropsch) efficiency and carbon footprint improvements for e-fuels: e-methanol; e-gasoline; e-kerosene; e-diesel; fertilizers.
	Gas and power	Synthetic natural gas for power; methanation process.
	Heat and feedstock	Process heating; hydrogen for refineries.

(*Continued*)

Hydrogen value chain	*Central themes*	*Potential R&D areas*
	Grid balance	Integration of heat pump technology.
End-use application	Power	Hydrogen/ammonia-fired gas turbines; ammonia co-firing in boilers.
	Mobility	Advanced fuel cells for mobility; fuel cells for heavy-duty transport.
		Low-purity hydrogen use: solid oxide fuel cells; direct ammonia fuel cells; hydrogen-fired internal combustion engine (ICE); ammonia ICE for shipping.
	Heavy industries	Hydrogen as a heat source for heavy industries; hydrogen integration in cement; aluminum, glass, mining; steel-direct iron reduction.
	Residential	Building heating with hydrogen burners; heat pumps for cooling and heating.
Hydrogen system and grid integration; hubs	Digitization	High-speed computing; AI; Industry 4.0 technologies. Smart grids.
	Hubs	Knowledge sharing and partnerships on industrial-scale hydrogen hubs.
End-of-life technologies; stranded assets	Circular economy	End-of-life of fuel cells and hydrogen products: alkaline water electrolysis, solid oxide fuel cells, and proton exchange membrane water electrolysis material and mineral retrieval/disposal; strategies for valorization stranded assets.

Notes

1 This chapter defines Europe as the 27 member states of the EU (i.e., Austria, Belgium, Bulgaria, Cyprus, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden), the United Kingdom, Switzerland, and additional members of the European Economic Area (i.e., Iceland, Lichtenstein, and Norway).

2 CBAM will be the first of its kind. It is designed to be in full compliance with World Trade Organization (WTO) rules. It will apply from 1 October 2023 but with a transition period where the obligations of the importer shall be limited to reporting. After an initial transit period, the European Commission shall assess whether to extend the scope to other goods at risk of carbon leakage, including organic chemicals and polymers, with the goal to include all goods covered by the ETS by 2030.

3 Interviews with Noé van Hulst (January 27, 2022) and Jose Miguel Bermudez Menendez (February 2, 2022).

4 Interviews with Constantine Levoyannis (Nel), October 13, 2021 and Jose Miguel Bermudez Menendez (IEA), February 2, 2022.

5 Constantine Levoyannis (Nel), October 13, 2021 and February 9, 2022.

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9

HYDROGEN IN CHINA

Crucial opportunities for transitioning to a low-carbon economy

Tianduo Peng, Xun Xu, Lining Wang, and Jiaquan Dai

Introduction

Hydrogen is a high-quality energy carrier that burns cleanly and efficiently as well as has versatile applications in transportation, industry, building, and power generation. As a potential solution for achieving decarbonization and climate change mitigation goals, it is expected to play a crucial role in the new wave of global energy and industrial evolution. China, the world's largest carbon emitter and hydrogen producer, is keen to expand the role of hydrogen in its future energy supply and decarbonization policy. Indeed, given the country's abundant renewable resources and vast domestic market for clean energy, it has great potential to develop a new energy system in which hydrogen plays a critical role. Hence, hydrogen has recently been at the forefront of public policy discussions in China, and significant resources have been dedicated to its technological research and market development. China's recent commitment to reach peak carbon emissions before 2030 and achieve carbon neutrality before 2060 has seen hydrogen gain even greater policy and market momentum. In light of this fast-changing landscape, this chapter reviews the strategic, production, application, and research aspects of hydrogen development in China to analyze how hydrogen can contribute to developing its low-carbon economy. It also explores the potential for mutually beneficial collaborations between China and Saudi Arabia in the new 'hydrogen era.'

The remainder of this chapter is organized as follows. The next section briefly discusses the strategies that China has adopted to promote hydrogen development. The third section describes recent trends in hydrogen production, distribution, and applications in China. The fourth section briefly discusses hydrogen-related research activities by state-owned enterprises, academia, and the private sector. The fifth section uses the case of Zhangjiakou to illustrate the latest developments in the

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hydrogen economy in China. The sixth section discusses potential opportunities for China and Saudi Arabia to collaborate in hydrogen development. The last section concludes.

Strategy

Hydrogen as an important pathway to achieve the low-carbon energy transition and green economic growth in China

The most fundamental driving forces for low-carbon hydrogen development in China are decarbonization and climate change mitigation. After committing to the Paris Agreement, China updated its climate goals in 2020 to achieve peak carbon emissions before 2030 and reach carbon neutrality before 2060. In late 2021, it released an action plan for reaching its peak carbon emissions goal (Communist Party of China Central Committee and the State Council of China 2021, State Council of PR China 2021). The new policy guidelines stipulate that decarbonization should be accelerated in all sectors through the application of clean energy; electrification; and carbon capture, utilization, and storage (CCUS) technologies. Hydrogen, as a high-quality carrier of renewable energy, is expected to play a critical role in decarbonizing energy- and carbon-intensive sectors such as industry and heavy-duty freight transportation, which would be difficult to decarbonize otherwise.

The coordinated development of hydrogen production and renewable energy generation offers a potentially viable solution to address China's energy security concerns. The country faces the dual challenge of promoting the low-carbon transition and meeting domestic growth in energy demand, with national energy consumption likely to increase by approximately 1 billion tons of standard coal equivalent (1 ton of coal equivalent = 29,307 gigajoules) before 2030 compared with the 2020 value (CNPC Economics & Technology Research Institute 2020, Duan et al. 2021, He et al. 2020). However, China's energy supply is highly dependent on fossil fuels, with over 70% of oil and 40% of natural gas imported (CNPC Economics & Technology Research Institute 2022).

Nonetheless, China has abundant renewable energy resources. The estimated exploitable energy from renewable sources (e.g., hydro, wind, and solar) amounts to 95.8 trillion kilowatt (kW) hour (kWh) annually. This is almost 13 times the country's total power consumption in 2020 (Wang et al. 2022). To reach the carbon neutrality target and reduce reliance on fossil fuel imports, the proportion of renewable energy in the energy mix must increase significantly during the 2020s. While most of China's renewable energy sources are located far from its densely populated coastal regions and power generation from renewable sources has inherent intermittency issues due to their inconsistent nature, hydrogen, as an easy-to-store and easy-to-transport energy carrier, could be used to remove the energy mismatch between supply and demand geographically and temporally, thereby improving the resilience of China's future energy supply.

In addition to accelerating the energy transition, hydrogen development may facilitate China's ongoing industrial and economic transformation. With a value chain spanning energy and chemical production to transportation and steel manufacturing, growing demand for hydrogen could benefit many. This includes raw materials and parts suppliers, equipment manufacturers, and service providers, among others. According to China Hydrogen Alliance (2019), the total annual output of China's hydrogen sector is projected to reach RMB 10 trillion (approximately $1.58 trillion) by 2050. Therefore, as growth in fossil fuel demand slows and China undergoes a systematic energy transition, the development of hydrogen and its associated technologies is well positioned to enable the country's new green economic development by creating new industrial value chains.

Government strategies on hydrogen development

In early 2022, China released its Medium- and Long-term Plan for the Development of the Hydrogen Industry (2021–2035), which proposed a new set of goals for the hydrogen sector to achieve in the next 15 years. In particular, the plan set detailed targets for 2025, such as achieving an annual production of 100,000 to 200,000 tons of green hydrogen and 50,000 hydrogen fuel cell vehicles (FCVs), while establishing a relatively complete hydrogen industrial value chain (National Development and Reform Commission & National Energy Administration of China 2022). Hydrogen produced from industrial by-products and renewable sources is expected to dominate the supply of new end-use applications in the near term. In the long run, the proportion of renewable-sourced hydrogen in total supply is expected to increase significantly. Hydrogen applications will also expand to multiple sectors, including transportation, energy storage, power generation, and the steel and chemical industries. Table 9.1 shows that most existing policies to support hydrogen development focus on developing hydrogen FCVs (China Center for International Economic Exchanges 2020, National Development and Reform Commission & National Energy Administration of China 2022). This is partly because long-distance road transportation is one of the most important yet difficult sectors to decarbonize in China and because hydrogen fuel cell technology as a potential solution has received the majority of policy and business attention.

According to the Energy-Saving and New Energy Vehicle Technology Roadmap 2.0 released by the China Society of Automotive Engineers (2021), the stock of hydrogen FCVs is expected to reach one million by 2035. The main applications of FCVs are in the commercial vehicle market, including coaches, heavy-duty trucks, and special-purpose vehicles (e.g., forklifts). Hydrogen is also expected to play a key role in other sectors, including energy storage, industry, and construction. Indeed, as shown in Table 9.2, demand for hydrogen could reach 60 million tons by 2050 and more than double that by 2060 (130 million tons). This would account for 20% of all end-use energy, while the ownership rate of medium- and heavy-duty fuel cell trucks could exceed 50% (China EV 100 2020, China Hydrogen Alliance 2021).

TABLE 9.1 Selected government policies for hydrogen development since 2015

Policy	*Year of release*	*Content*
Medium- and Long-term Plan for the Development of the Hydrogen Industry (2021–2035)	2022	Proposing phased targets for the development of the hydrogen value chain in 2025, 2030, and 2035
New Energy Vehicle Industry Development Plan (2021–2035)	2020	Proposing systematic plans for the development of hydrogen fuel cells
Notice on Launching the Demonstration Application of Fuel Cell Vehicles	2020	Providing incentives to eligible urban agglomerations for the research and demonstration application of key fuel cell technologies
Energy Law of the People's Republic of China (Draft for Solicitation of Comments)	2020	Defining hydrogen as a type of energy
Government Work Report	2019	Advancing the construction of hydrogen refueling infrastructures
Automobile Industry Mid- and Long-term Development Plan	2017	Proposing a technological roadmap for hydrogen FCVs, supporting the technological breakthrough of the whole industrial chain, and progressively expanding the scope of the pilot demonstration
National Development Plan for Strategic Emerging Industries during the 13th Five-Year Plan Period	2016	Promoting the R&D and industrialization of hydrogen FCVs in a systematic manner and realizing mass production and large-scale demonstration applications by 2020
Energy Technology Reform Action Plan (2016–2030)	2016	Taking fuel cell technology innovation as a key task by promoting R&D in fuel cells, fuel cell distributed power generation, hydrogen production, storage and transportation, and hydrogen refueling stations
Made in China 2025	2015	Completing hydrogen production and refueling infrastructures by 2025 and achieving regional small-scale operations for FCVs

TABLE 9.2 Targets for the hydrogen industry in China

Item	*2025*	*2035*	*2050*
Hydrogen energy demand (million tons)	30	40	60
Industrial output value (trillion yuan)	1	5	12
Hydrogen refueling stations	200	2000	12000
FCVs (million)	0.1	1	30

Source: China Hydrogen Alliance (2019), China EV 100 (2020), and The State Council (2020).

The central government has implemented several measures to support its policy directives. For example, a fuel-cell electric vehicle (FCEV) demonstration city cluster program has been launched to promote pilot projects and the early adoption of FCVs across China, including the provision of a credit reward system. Depending on the year of purchase, each FCV can be rewarded between 0.9 and 1.3 credits, with each credit being equivalent to RMB 100,000. For each eligible city cluster, total rewards are capped at 17,000 credits (Ministry of Industry and Information Technology et al. 2021). Since its implementation, the program has received almost 20 applications and has approved five city clusters for FCEV demonstration. At the provincial and municipal levels, governments have been even more proactive in promoting hydrogen development. Apart from being an essential component of the low-carbon transition, local governments consider hydrogen to be an important opportunity to promote economic growth and facilitate industrial restructuring. By the end of 2021, more than half of all provinces and over 30 municipalities in China had released specific plans to support hydrogen development. Table 9.3 shows some of the policy targets by province and municipality.

To kickstart local hydrogen development and attract private investment, governments often provide tax incentives and subsidies to procure FCVs and develop the hydrogen infrastructure. For example, a hydrogen refueling station with a capacity of over 500 kilogram (kg) per day would cost RMB 10–20 million in China (China EV 100 2020). In this case, local governments may provide a subsidy of between RMB one and four million for each refueling station to accelerate the construction of these infrastructures.

Overall, policymaking on the development of the hydrogen sector has increased substantially in recent years. However, challenges remain for stakeholders at all levels. On the one hand, the long-term development pathway for hydrogen needs

TABLE 9.3 Plans for FCVs in selected provinces

Province/city	*Year*	*Number of FCVs*	*Number of stations*
Beijing	2025	10,000	74
Guangdong	2022	Demonstration operation of hydrogen FCVs	300
Jiangsu	2025	10,000	50
Shandong	2025	10,000	100
Shanghai	2023	10,000	100
Zhejiang	2022	1000	30
Chongqing	2025	5000	10

Source: Beijing Municipal Bureau of Industry and Information Technology (2021), Chongqing Municipal Commission of Economy and Information Technology (2021), Government Office of Shandong Province (2020), Guangdong Provincial Development and Reform Commission (2020), Industry and Information Technology Department of Jiangsu (2019), Shanghai Municipal Commission of Economy and Information Technology (2020), and Zhejiang Provincial Development and Reform Commission (2021).

to be continuously optimized and improved as the hydrogen industry develops. This is to minimize the risk and uncertainty facing the industry and investors. On the other hand, market resources and policy efforts, especially those of local governments, focus disproportionately on hydrogen applications in the transportation industry. Meanwhile, other sectors have received less attention. Thus, China must adopt a more comprehensive and coordinated approach to devise and implement hydrogen policies to tap into its potential in other sectors. This will help it achieve a more balanced development of hydrogen applications across the value chain.

Production, distribution, and application

Reliance on fossil fuels for producing hydrogen in China

China is the world's largest producer of hydrogen, with annual output recently exceeding 30 million tons (China Hydrogen Alliance 2021), amounting to approximately one-third of global hydrogen production (International Energy Agency 2019). However, China's hydrogen output is primarily produced from fossil fuels and consumed as an industrial feedstock. Meanwhile, the scale of hydrogen production from clean energy remains small. As shown in Table 9.4, nearly 70% of hydrogen in China is produced from coal, natural gas, and petroleum. Approximately 30% comes from industrial by-product gases and water electrolysis accounts for less than 1% of output (China EV 100 2020).

While existing hydrogen production capacity is sufficient to meet current domestic demand, according to the new 2021–2035 plan, China's future hydrogen supply will transition to be based more on renewables. Thus, it will bypass blue hydrogen, which uses natural gas to produce hydrogen and CCUS technologies to capture and store CO_2 emissions underground owing to the high cost of applying CCUS systems in China. For example, the cost of producing hydrogen using coal gasification would be 1.5 times to twice as high if CCUS technologies were adopted (CNPC Economics & Technology Research Institute 2021, International

TABLE 9.4 Source of hydrogen production

Raw materials and methods of producing hydrogen		*Global*	*China*
Fossil fuels	Coal	18%	43%
	Natural gas (steam methane reforming)	48%	16%
	Oil	30%	13%
Hydrogen from industrial by-product purification	Coke oven gas, chlor–alkali tail gas, etc.	/	28%
Hydrogen from electrolytic water	/	4%	<1%
Other	Biomass, photocatalysis, etc.	/	/

Source: Tsinghua University and China EV 100 (2020).

Energy Agency 2019, U.S. Department of Energy 2020). Another important determinant is China's long-term plan to move to a renewable-dominated energy mix that disincentivizes the use of fossil fuels for producing hydrogen.

In accordance with this production roadmap, China's fossil fuel-based hydrogen supply chain is expected to maintain its primary role in the early stages of the future transition owing to its low production costs and proximity to the market. Endowed with abundant coal resources, China has developed a large coal chemical industry with widely distributed capacity and substantial annual coal-to-hydrogen output. By contrast, although steam methane reforming, a natural gas-based hydrogen production technology, is also mature and widely used, producing hydrogen from natural gas is not cost-effective in China for a number of reasons. These include limited natural gas availability, high sulfur content, and significant impact of natural gas prices on hydrogen production costs. Hence, producing hydrogen using steam methane reforming may only be cost-competitive in regions endowed with abundant natural gas resources.

In the long run, water electrolysis using renewable energy holds great promise for producing hydrogen and is expected to play a dominant role in the hydrogen supply. The three technology options available, namely, alkaline hydrolysis, proton exchange membrane electrolysis, and high-temperature steam electrolysis, are at different stages of maturity. Producing hydrogen production using electrolysis will eventually become cost-effective in China. With China's potential to produce 95.8 trillion kWh of renewable energy annually from solar, wind, hydro, geothermal, and biomass power, using just 15% of total renewable output could produce 100 million tons of hydrogen using electrolysis, which would fully meet end-user demand. Other technologies such as coal-to-hydrogen production combined with carbon capture and storage (CCS), bio-hydrogen production, and photocatalytic water splitting will likely become effective supplements to water electrolysis production (Figure 9.1).

Necessary improvements in hydrogen storage, transmission, and distribution

The most common approach for transporting hydrogen over short distances in China is to use tube trailers at a pressure of 200 bar. For long distances, liquid tanker trucks with higher storage pressures and hydrogen pipelines are much more economical and therefore desired. However, owing to technical constraints, hydrogen transportation at a pressure of 500 bar by road is rare, and the application of cryogenic liquid hydrogen tanker trucks is also limited.

The length of existing hydrogen pipelines in China, mostly dedicated to refineries, is slightly over 100 kilometers (km). This is less than 10% of those in Europe and the United States owing to the high initial investment, dependence on imports of expensive composite materials, and insufficient application scenarios. Cities across China have recently explored the option of transporting hydrogen

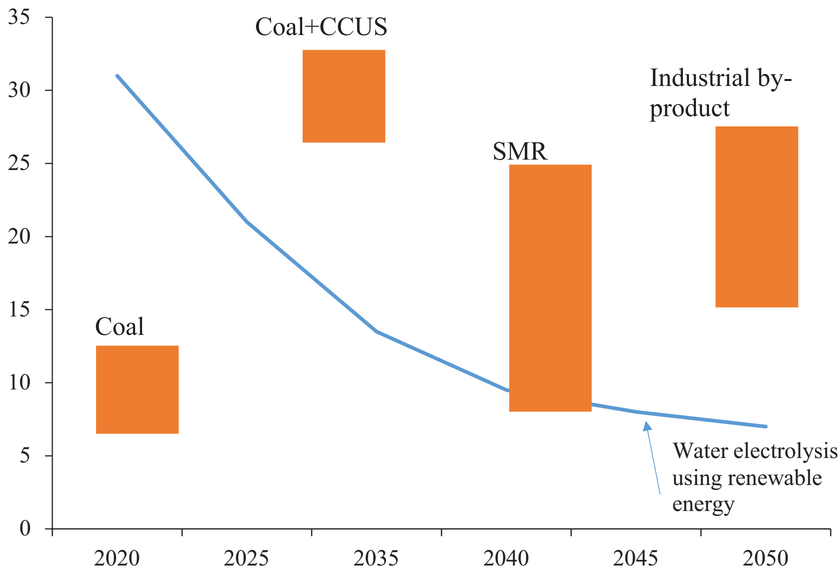

FIGURE 9.1 Cost range of hydrogen production technologies (RMB per kg of hydrogen).

Source: CNPC Economics & Technology Research Institute 2020.

using existing gas networks by blending it with natural gas. One direct application of the gas mixture is as a fuel gas for kitchen stoves and internal combustion engines. The city of Zhangjiakou, for instance, has launched a pilot project exploring the possibility of injecting 4 million cubic meters (m^3) of hydrogen into an urban gas grid to use mixed gases for cooking and as a fuel for hydrogen enriched with compressed natural gas vehicles. Another potential application is the separation and purification of hydrogen from the transported gas mixture and its reuse in fuel cells and power generators. However, such cases are rare in China owing to the high technical barriers and costs.

Several issues arise when hydrogen is blended into the existing natural gas infrastructure. Hydrogen may cause cracking and leakage in pipes because of its impact on pipeline materials. Depending on the equipment connected to the network, hydrogen can only be blended into natural gas up to a certain threshold. Additionally, separating hydrogen from natural gas is costly despite its low efficiency. Therefore, large-scale applications require dedicated long-distance hydrogen pipelines. For example, the construction of a new hydrogen transmission network located in Hebei Province has recently begun. This network will be longer than any existing hydrogen pipeline in China (145 km) and primarily used to transport hydrogen from north to south in the Beijing-Tianjin-Hebei region. Meanwhile, the newly founded PipeChina, the largest operator of domestic oil and gas pipeline networks in China, has established the Hydrogen Transmission, Development, and Innovation Consortium. Its primary objective is to combine the efforts of businesses, academic and research institutions, and other key stakeholders in the hydrogen value chain to develop new hydrogen transmission networks and overcome potential technical challenges.

In terms of the distribution network, as of the end of 2020, China had built 118 hydrogen refueling stations, of which 101 were already operating. As high-pressure hydrogen storage is costly and not widely available, most refueling stations operate at a pressure of 350 bar. The vast majority of existing stations rely on an external hydrogen supply, with only the minority benefitting from the capacity to produce hydrogen on site. For example, one station in the city of Dalian can produce hydrogen using a hybrid wind–solar power generation system. Another in the city of Foshan in south China can produce hydrogen simultaneously from natural gas and water electrolysis at the rates of 500 normal meter cubed per hour (Nm^3/h) and 50 Nm^3/h, respectively, with the latter being powered by rooftop solar panels.

With strong policy support, the development of a new refueling infrastructure may see explosive growth in the coming years. One potential trend in developing the refueling infrastructure is the increasing deployment of petrol/hydrogen multi-fuel stations. For instance, 17.9% of new hydrogen refueling stations constructed in 2019 were multi-fuel stations and this proportion increased to approximately 50% in 2020 (Figure 9.2). The China Petroleum & Chemical Corporation, the owner and operator of China's largest petrol refueling network, is planning to renovate and convert many of its petrol stations into petrol/hydrogen multi-fuel stations.

New hydrogen demand driven by transportation

The transportation sector has been the major driver of new hydrogen demand in China. With the exception of 2020 as a result of the COVID-19 pandemic, sales of FCVs have rapidly increased annually since 2015 (Figure 9.3). Cumulative sales

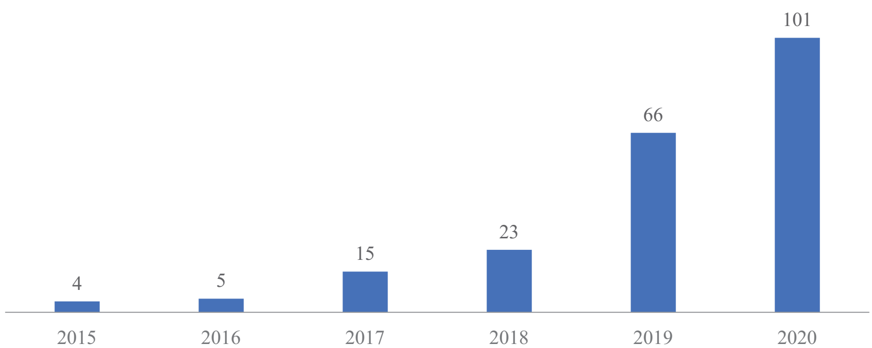

FIGURE 9.2 Number of hydrogen refueling stations in operation in China.

Source: CNPC Economics & Technology Research Institute (2020).

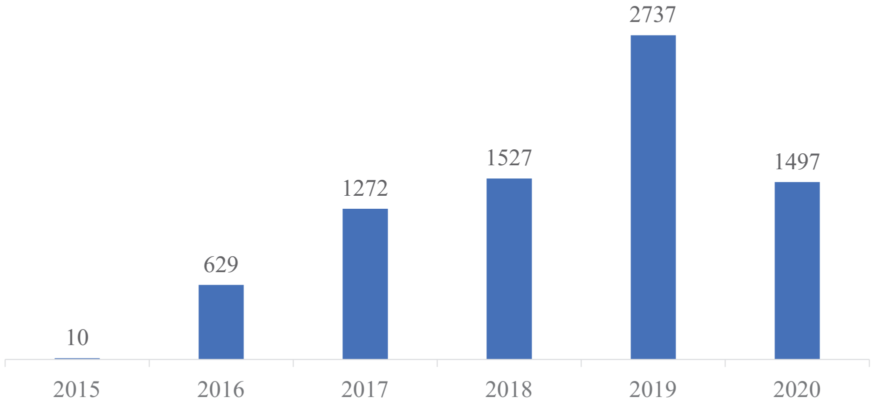

FIGURE 9.3 Sales of FCVs in China.

Source: China Automotive Technology Research Center (2021).

of FCVs have exceeded 7,000, second only to sales in South Korea and the United States (China Automotive Technology Research Center 2021). Unlike countries that focus on hydrogen applications in passenger mobility, commercial applications of FCVs are prioritized in China. Commercial FCVs such as hydrogen trucks and buses dominate existing sales. The commercial demonstration of FCVs has been conducted in 17 provinces in China and over 1,000 hydrogen FCVs have been deployed in several regions (e.g., Guangdong and Shanghai).

Although hydrogen-powered heavy-duty trucks are likely to achieve cost competitiveness by around 2035, as shown in Figure 9.4 (CNPC Economics & Technology Research Institute 2021), hydrogen technology remains at an early stage and is not cost-competitive compared with existing technologies. Market demand for new hydrogen applications remains low overall, and hydrogen supply, use, and distribution vary significantly across the regions. Mature business models must thus be developed for various segments of the value chain (e.g., production, storage, and transportation) to reduce the high utilization cost. For example, the vehicle purchase and fuel costs of a 42-ton hydrogen-powered heavy-duty truck in China are respectively 230% and 100% higher than their diesel-powered counterparts. The resultant total cost of owning and operating a hydrogen heavy-duty truck over its life cycle is approximately 150% higher than that of a regular internal combustion engine truck. In the long run, with continued advances in technology, efficiency improvements in the hydrogen supply chain, and economies of scale, utilization costs are expected to decrease significantly. For example, the study conducted by Tsinghua University suggested that the cost of hydrogen fuel cell systems may be reduced by 80% in the next decade (Minggao Ouyang 2021). Another estimation found that hydrogen-powered heavy-duty trucks may reach life cycle cost parity with diesel-powered trucks before 2030 (Hydrogen Council 2020).

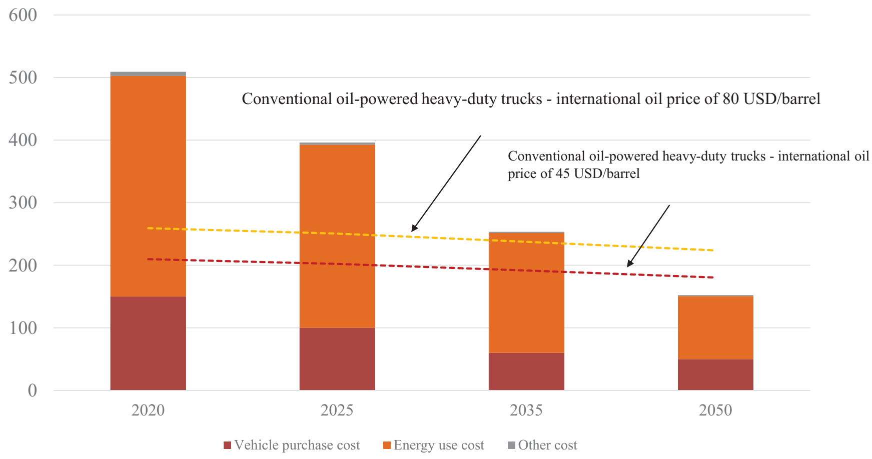

FIGURE 9.4 Comparison of the life cycle costs between hydrogen-powered heavy-duty trucks and traditional oil-powered trucks (RMB 10,000/truck).

Source: CNPC Economics & Technology Research Institute (2020).

Apart from FCVs, several other ongoing hydrogen applications in transportation and other sectors in China may reach commercial maturity.

- **Fuel cell trams:** At the end of 2019, the city of Foshan in Guangdong Province started operating the world's first commercial hydrogen fuel cell tram line. The 17.4-km tram line operates four fuel cell-powered trams daily. The daily recharge capacity of the refueling station for the tram line is 1,000 kg of hydrogen and each tram, when fully refueled, can run for up to 125 km.
- **Fuel cell forklifts:** Hydrogen fuel cell-powered forklifts could be an ideal replacement for petrol- and LPG-powered forklifts. Several cities such as Tianjin and Foshan have offered monetary incentives for the purchase or rental of fuel cell forklifts.
- **Inland waterway:** The application of hydrogen fuel cell technology is being explored for river/lake cruises and inland shipping. The Outline for the Development of Inland Shipping issued by the Ministry of Transport in 2020 proposes the development of pure electric and fuel cell-powered vessels. Moreover, a 500-kW inland hydrogen fuel cell ship is being developed by the China State Shipbuilding Corporation. According to the China Waterborne Transport Research Institute, the number of newly built hydrogen fuel cell vessels and existing vessels to be modified to incorporate a hydrogen fuel cell powertrain (primarily short-distance inland cruise ships) could reach 400 and 200 by 2025, respectively.
- **Aviation:** Research on hydrogen-powered aircraft is accelerating decarbonization in the aviation sector. For example, a test flight of a manned hydrogen

fuel cell plane was successfully conducted in 2017. However, neither hydrogen internal combustion engines nor hydrogen fuel cells, the two technology options currently available, are likely to enter commercial applications soon.

- **Steel production:** Iron and steel production accounts for approximately 15% of China's carbon emissions, making it the largest domestic carbon-emitting manufacturing sector (Ren et al. 2021). Hence, to reach the carbon neutrality target, the iron and steel sector in China must significantly reduce—if not completely eliminate—its carbon emissions. Decarbonizing this sector using hydrogen has entered the commercial stage. The Hebei Iron and Steel Group, a leading Chinese steel producer, is planning to build a 600,000-ton direct reduced iron (DRI) plant, the world's first such production plant powered by hydrogen-enriched gas. The emission intensity of the new plant drops to 125 kg of carbon dioxide (CO_2) per ton of DRI, which is approximately one-twelfth of the amount emitted under conventional production methods. Meanwhile, new low-carbon technology is being developed by Tsinghua University, the China National Nuclear Corporation, and the China Baowu Steel Group for manufacturing steel using hydrogen produced with high-temperature gas-cooled nuclear reactors. As the Chinese government has restricted the development of energy- and carbon-intensive industrial projects, hydrogen application in steelmaking is expected to accelerate. According to estimates by China Hydrogen Alliance (2021), annual hydrogen consumption in the iron and steel sector is expected to exceed 14 million tons by 2060.
- **Combined heat and power (CHP):** For heating applications in the building sector, heat pumps and heating powered by distributed renewable energy systems have received much more policy attention in China than the potential use of hydrogen for fuel cell CHP systems. Nevertheless, several 100-kW fuel cell CHP pilot projects have begun, with effective electric efficiency reaching 54% and total system efficiency rising above 90%.
- **Power generation:** China has a long-term aim to build a renewables-based energy system, with wind, solar, and hydropower becoming the primary sources of energy. Given the cost and other constraints in its value chain, hydrogen is expected to become a secondary option for power production. Its main applications would lie in energy storage, peak shaving, emergency, and standby power systems. Two coastal provinces, Guangdong and Fujian, have started demonstrations of emergency power vehicles with hydrogen fuel cell generators and hydrogen-powered 5G base stations, respectively.
- **Renewable methanol:** A demonstration project of renewable methanol production in the city of Lanzhou can produce low-carbon methanol through the synthesis of CO_2 and hydrogen using solar-powered water electrolysis. The two electrolyzers are powered by 10 megawatt solar power-generating facilities and can produce hydrogen at 1,000 Nm^3/h.

Research priorities

The high utilization costs, unsatisfactory technical performance, and limited commercial applications are all crucial barriers to hydrogen development in China. The central government, in collaboration with leading academic institutions, state-owned enterprises, and other key stakeholders, has increased its support for R&D to address these issues. The top research priorities include improving the performance of FCVs; reducing the costs of hydrogen production via water electrolysis and from fossil fuels with the adoption of CCUS technologies; and promoting pilot and demonstration projects of steel production using hydrogen. Additionally, research is evaluating the environmental impacts of hydrogen use, developing related policy regulations and standards, and designing future technology roadmaps and development pathways. Table 9.5 shows the key technical and economic performance targets for hydrogen FCVs.

The China Hydrogen Alliance, jointly established by China's leading state-owned enterprises and academic and financial institutions, is a consortium consisting of over 100 member institutions from all segments of the hydrogen value chain. It seeks to promote collaboration on hydrogen technology innovation, establishment of standards and safety codes, and implementation of commercial demonstrations. Apart from regular research publications to raise public awareness and inform stakeholders, the Alliance plays a critical role in influencing policymaking on hydrogen development. In late 2020, it released one of the world's first industrial standards for low-carbon and clean hydrogen (China Hydrogen Alliance 2020), which offers an important reference for decision-makers in national and regional governments to formulate future hydrogen policies.

TABLE 9.5 Technical and economic indicators of FCVs in China.

	2030	*2035*
Performance	The cold start temperature reaches −40°C and the performance of FCVs reaches that of hybrid vehicles	The cold start temperature reaches −40°C and the performance of FCVs is the same as that of internal combustion engine vehicles
Commercial vehicle	Mileage >500 km	Mileage >800 km
	Hydrogen consumption by buses ≤5.5 kg/100 km	Hydrogen consumption by heavy-duty trucks ≤10 kg/100 km
	Lifespan >0.4 million km, cost ≤ RMB 1 million	Lifespan >1 million km, cost ≤RMB 0.5 million
Passenger car	Mileage >650 km	Mileage >800 km
	Hydrogen consumption ≤1 kg/100 km	Hydrogen consumption ≤0.8 kg/100 km
	Lifespan >0.25 million km, cost ≤RMB 0.3 million	Lifespan >0.3 million km, cost ≤RMB 0.2 million

Source: China Society of Automotive Engineering 2021.

In addition to state-led consortia that promote knowledge and share resources between public and private sector partners, academic institutions have played an important role in incubating new hydrogen startups and attracting private investment for promising technology innovations. For example, SinoHytec, a spinoff startup from Tsinghua University, has become one of China's leading manufacturers of automotive fuel cell systems that range in rated power from 30 kW to 240 kW. It has also become a major supplier of fuel cell power systems to commercial vehicles such as buses, coaches, and delivery vehicles in China.

Case study

Many cities across China have started hydrogen pilot projects, among which Zhangjiakou, a co-host city of the 2022 Beijing Winter Olympics in northern China, offers an interesting case study for exploring the potential of the 'hydrogen economy.' Located in the northwestern part of Hebei Province less than 200 km from Beijing, the city is the first and only national-level renewable energy demonstration zone in China approved and established by the State Council.[1] The opportunity to jointly host the Winter Olympic Games with Beijing provides an excellent case for the commercial demonstration of hydrogen applications in a number of areas and hence offers substantial incentives to kickstart the development of the city's hydrogen sector. A number of policies have been announced, including the Zhangjiakou Hydrogen Development Plan 2019–2035 and Promotion and Implementation Plan for Zhangjiakou's Hydrogen Sector in the 14th Five-year Plan Period.[2] In late 2021, the Zhangjiakou-spearheaded Hebei FCEV demonstration cluster was approved by the central government as one of five urban clusters in China selected to pilot FCV applications.[3] These policy directives have led to the establishment of a long hydrogen value chain in Zhangjiakou, quickly transforming it into one of the nation's leading hydrogen development centers.

The largest hydrogen application in Zhangjiakou is in the transportation sector. Between 2018 and 2021, 444 fuel cell buses and 40 fuel cell delivery vehicles were deployed, carrying 62 million passengers and traveling more than 21 million km. During the 2022 Winter Olympics, the city operated a fleet of 710 FCVs to transport athletes and staff between competition zones, reducing over 1,400 tons of carbon emissions.[4] According to the Implementation Plan of the Hebei FCEV Demonstration Cluster, 1,130 hydrogen-powered buses, delivery vehicles, heavy-duty freight trucks, and refuse trucks are expected to be deployed in the city during the next four years of the demonstration period.[5]

Green hydrogen is produced locally to meet demand for Zhangjiakou's FCVs. Four production facilities produce green hydrogen using wind and solar power, which are abundant in the region. The production capacity of green hydrogen is 6,700 Nm^3/hour, with an average cost of approximately RMB 30/kg.[6,7] With more investment in the line and the anticipated growth in production facilities, hydrogen output may exceed 50,000 tons over the next four years, halving the average production cost.[8]

Approximately 10 hydrogen refueling stations have now been constructed in the city, with charging capacity estimated to be over 8.9 tons every 12 hours.[9,10] The majority of these stations charge at a pressure of 350 bar, although some are equipped with a 700-bar pressure charging capacity, while two have refueling capacity for vehicles of other fuel types, including electric vehicles and internal combustion engine vehicles. More multi-fuel stations are anticipated to be developed as Zhangjiakou expands its hydrogen refueling network. In addition, more hydrogen refueling stations are expected to be deployed along the expressways connecting the city with Beijing and Shijiazhuang, the capital of Hebei Province, which could make them the first fully operational intercity 'hydrogen expressways' in China.[11]

In addition to production, distribution, and public transit applications, Zhangjiakou has attracted investment from several other companies in the hydrogen space. Projects in the pipeline include manufacturing facilities for fuel cell engines, fuel cell stacks and components, FCVs, and hydrogen storage equipment.[12] According to the Zhangjiakou Hydrogen Development Plan 2019–2035, the total output of the city's hydrogen sector is anticipated to reach RMB 170 billion (approximately $25.3 billion) by 2035, creating more than 35,000 jobs.[13]

Potential for hydrogen collaboration between China and Saudi Arabia

China and Saudi Arabia have already developed long-standing economic relationships. China has been the Kingdom's largest trade partner since 2011 and has recently become the largest oil buyer.[14] As both countries are seeking to develop a full-fledged hydrogen economy, a broad range of opportunities for expanding their existing collaboration into the new hydrogen space exist.

On the supply side, both countries have formulated ambitious plans to produce a significant amount of hydrogen using renewable energy. However, the current cost of green hydrogen production using either solar or wind power remains high, which must be reduced to enable production on a larger scale. Such cost reductions could be driven by the continued decline in the costs of renewable energy and scaling up of green hydrogen manufacturing, which would in turn drive down the cost of water-splitting equipment such as electrolyzers. China is the world's largest producer of solar panels and wind turbines as well as the largest market for both types of renewable energy. With the country's ambitious plan and huge potential for green hydrogen, the extraordinary size of its market could lead to a rapid decline in production costs, which would then benefit Saudi Arabia as a future supplier of renewable-sourced hydrogen. Meanwhile, the Kingdom could facilitate this transition by investing in China's green hydrogen industry and accelerating the cost reduction of new technologies such as proton exchange membrane electrolysis. Additionally, China could benefit from collaborating with Saudi Arabia on CCUS projects, as the Kingdom has pioneered its applications.[15] CCUS can be used for both blue hydrogen production and enhanced oil recovery in suitable regions in China.

There are several other opportunities to explore hydrogen utilization. One area of potential collaboration is low-carbon steelmaking. The development of real estate properties and public infrastructure has played an essential role in the economic growth of Saudi Arabia. With iron and steel being critical materials for housing and infrastructure, the Kingdom has maintained a large amount of iron and steel imports, especially from China, the world's largest steel exporter.[16] The national socioeconomic transition plan, Vision 2030, has unleashed close to a trillion dollars of real estate and infrastructure projects since 2016.[17] Given the carbon-intensive nature of steelmaking, developing low-carbon steel manufacturing capacity in the Kingdom would align with both its economic plan and its climate change mitigation goals. This is particularly so given that Saudi Arabia seeks to use its domestic mineral resources and diversify its economy. In 2021, Saudi Aramco signed a memorandum of understanding with China's Baowu group, the world's largest steelmaker, for a potential world-class steel production facility that would use the low-carbon DRI-electric arc furnace process.[18] This joint project could serve as an important demonstration of industrial hydrogen use and kickstart new hydrogen applications within the Kingdom.

The transportation sector offers an additional opportunity for collaboration. With its large land mass and sparse population distribution, Saudi Arabia has long been heavily reliant on road vehicles for domestic freight transportation and passenger mobility. In fact, oil demand by the transportation sector has significantly contributed to the Kingdom's domestic oil consumption. This has made the country one of the world's top oil consumers at both the aggregate and the per capita levels. Saudi Arabia has recently aimed to curb fast-growing domestic oil consumption and reduce carbon emissions. This has been conducted through a number of policy measures such as improving fuel efficiency and increasing gasoline prices.[19] As mentioned previously, China has been actively developing hydrogen fuel cell technologies and promoting their application in the commercial vehicle sector, especially for freight trucks, buses, and coaches. Indeed, China has the largest commercial FCV fleet worldwide.[20] Hence, with Saudi Arabia's latest climate pledge to reach carbon neutrality by 2060, the Kingdom could benefit from collaboration with China to accelerate the deployment of commercial FCVs and reduce transportation fuel consumption and carbon emissions.

Given the Kingdom's clearly structured road transport routes, hydrogen FCVs could be particularly well suited for long-haul freight transportation between major coastal logistics hubs and inland metropolitan regions. In March 2022, the Saudi Arabian Industrial Investments Company, Dussur, and Tatweer Educational Transportation Services Company signed a joint venture agreement with China's CHTC KINWIN Automobile to establish a new bus manufacturing facility in Jeddah. The joint venture will manufacture and assemble buses using internal combustion engines, pure electric, and hydrogen fuel cell engine technologies. With an annual production capacity of 3,000 buses, the new project is expected to meet rising domestic demand for buses from multiple sectors such as Hajj and Umrah, education, tourism, and public transport. It is also expected to help improve the local content of the transportation sector and accelerate the development of the country's automotive industry.[21,22]

Conclusion

Global efforts to combat climate change and the trend toward low-carbon energy transitions have brought renewed momentum to hydrogen development. As the world's largest hydrogen producer and carbon emitter, China has been actively exploring new approaches to use hydrogen to fulfill its targets for climate change, economic transition, and energy security. Hydrogen is anticipated to become an integral part of China's future energy mix and play an important role in the transportation, industrial, and power generation sectors, among several others. However, to achieve their long-term objectives, governments, public and private sector players, and the research community must take joint actions to overcome a number of barriers and challenges.

At the policy level, China must expand its current medium- and long-term hydrogen plans to create a full-fledged national strategy to guide future hydrogen development. Within the value chain, the storage and transmission of hydrogen remain underdeveloped, which has contributed to the high cost of utilization significantly. In terms of future hydrogen supply, although China is the world's largest producer of renewable energy, to become a leader in low-carbon hydrogen production, significant resources are still needed to accelerate the R&D of related technologies and scale up production. Finally, from the demand perspective, there are inadequate application scenarios to justify the high production and utilization costs of low-carbon hydrogen. More pilot projects and demonstrations at a larger scale are required to enable a positive feedback loop and make the hydrogen supply chain self-sustainable.

However, as long-standing economic and energy partners, China and Saudi Arabia are well positioned to use their rich natural resources and strong industrial capabilities to jointly develop the hydrogen economy. Endowed with abundant renewable resources and favorable geological conditions, Saudi Arabia has the potential to become the world's leading supplier of carbon-neutral hydrogen. To optimize its economic structure and build a low-carbon economy, the Kingdom has initiated many new economic endeavors that may offer excellent business cases to kickstart and demonstrate new hydrogen applications. Hence, a new window of opportunity has emerged for collaboration between the two nations. China and Saudi Arabia can strengthen their industrial cooperation and jointly invest in new hydrogen technologies to enable partnerships in the clean hydrogen era.

Notes

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10

THE EVOLVING HYDROGEN ECONOMY IN THE UNITED STATES

Naomi L. Boness and Gireesh Shrimali

Introduction

The public's desire to decarbonize is a strong policy driver, and hydrogen has the potential to reduce emissions well beyond its traditional uses (e.g., refining and fertilizer production). Indeed, since the Paris Agreement, hydrogen has garnered considerable attention in the United States as a way to abate emissions in sectors that, historically, have been difficult to decarbonize. However, given that the US federal hydrogen program has now been running for over two decades, whether this hype surrounding hydrogen will ultimately result in a large hydrogen economy remains unknown (US DOE 2001, 2002).

The United States produces more than 10 million metric tons of hydrogen per year, equivalent to 0.1% of total energy demand (US DOE 2020a). In 2020, the refining of petroleum products accounted for 68% of pure hydrogen consumption in the country and fertilizer production, 21% (NREL 2020). The primary centers for hydrogen production for refining are along the Gulf Coast in Texas and Louisiana as well as California. Smaller distributed hydrogen production centers for the agricultural sector are scattered across the mid-western and northeastern states.

Hydrogen demand can potentially reach close to 50 million metric tons in the United States by 2050, resulting in approximately 10% reduction in emissions relative to 2005 levels (US DOE 2023).

Much like Saudi Arabia, the primary energy sources required to produce low-carbon hydrogen are abundant in the United States, from renewable electricity sources to cheap natural gas coupled with geologic carbon storage capacity. Furthermore, the numerous US companies in the transportation and industrial sectors with expertise in many aspects of the hydrogen value chain are working to lower costs and develop new markets.

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US hydrogen strategy and policy at the federal and state levels

In the United States, hydrogen strategy and policy exist at both the federal level, applicable to the entire country, and the state level. In this section, we explore the federal strategy and review states' policies, with a focus on the key strategies of California, the most aggressive state in setting decarbonization targets and implementing policy. In particular, we discuss how California's policy has spurred the development of a hydrogen transportation market.

Federal strategy

In June 2023, under the Biden–Harris Administration, the Department of Energy (DOE) published the final version of the US National Hydrogen Strategy and Roadmap. The roadmap prioritizes three key strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit for the United States. These three strategies are to:

- Target strategic, high-impact uses of clean hydrogen to ensure its utilization in the highest value applications and where no deep decarbonization alternatives exist. Specific markets include the industrial sector, heavy-duty transportation, and long-duration energy storage to enable a clean grid.
- Reduce the cost of clean hydrogen through such efforts as the Hydrogen Energy Earthshot launched in 2021. This program aims to catalyze both innovation and scale, thus stimulating private sector investment, spurring development throughout the hydrogen supply chain, and reducing the cost of clean hydrogen drastically. Efforts will also address critical material and supply chain vulnerabilities and design for efficiency, durability, and recyclability.
- Focus on regional networks or 'hubs' that can produce clean hydrogen production at the large scale and develop a critical mass infrastructure.

The United States is targeting a 50%–52% CO_2 reduction by 2030 (compared with 2005 levels) and 100% carbon-free electricity by 2035. Specifically, the Strategy depicts potential scenarios for the end use of clean hydrogen in 2030, 2040, and 2050, enabling at least 20 million metric tons per year by 2040 and 50 million metric tons per year by 2050, as Figure 10.1 shows (US DOE 2023).

Interestingly, the Strategy follows a technology-neutral approach, with electrolysis, nuclear, reforming, pyrolysis, and waste all mentioned as possible production pathways. Simultaneously, there are clear targets for hydrogen fuel cells, namely, \$80/kW for trucks and \$900/kW for stationary use. By contrast, clear performance targets for hydrogen derivatives (ammonia, methanol, steel, PtL) are lacking. Finally, several actions toward quantifying hydrogen leakage and its climate impact are mentioned. The federal government, which focuses on technology development, provides a comprehensive hydrogen strategy under the

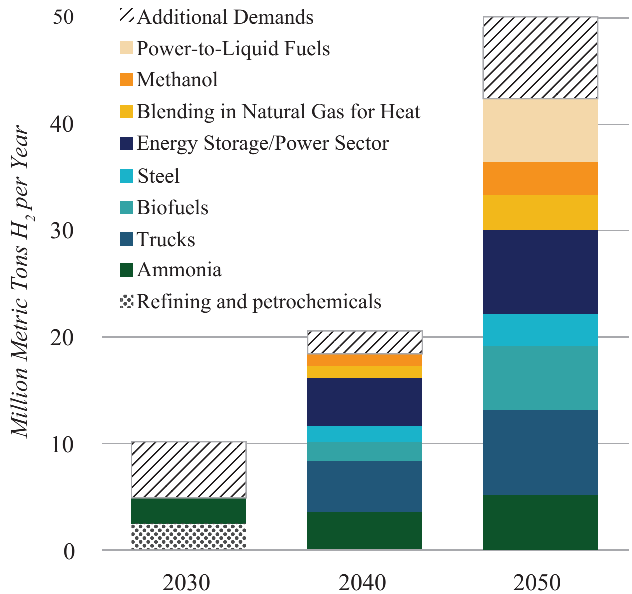

FIGURE 10.1 Potential scenarios for the end use of clean hydrogen in the United States in 2030, 2040, and 2050.

Source: US DOE (2023).

H2@Scale program (US DOE 2020a, 2020b). This program is the latest iteration of a federal hydrogen strategy that goes back more than two decades (US DOE 2001, 2002). At the federal level, the primary motivation for pursuing hydrogen is to decarbonize hard-to-abate sectors. Other considerations include diversifying supply, maintaining energy security, meeting future energy demand, and ensuring resilience to climate events and other threats (US DOE 2020b). However, the recent federal strategy focuses on meeting US demand through the domestic production of hydrogen.

H2@Scale, launched by the DOE in 2016, is a comprehensive development strategy within the framework of the existing DOE hydrogen portfolio, addressing the entire hydrogen value chain with a focus on integrated systems at scale. It provides a targeted approach to resolve the identified technology and deployment challenges of hydrogen, focusing on production; transport; storage; delivery; conversion; integration; manufacturing and supply chains; safety, codes, and standards; and education and workers (US DOE 2020b).

As Figure 10.2 illustrates, hydrogen provides more options across sectors and can complement the conventional grid and natural gas infrastructure in the United States. Rather than only 'electron-to-electron' pathways such as the electric grid to batteries, hydrogen can be stored and used where electrification may be challenging (US DOE 2023).

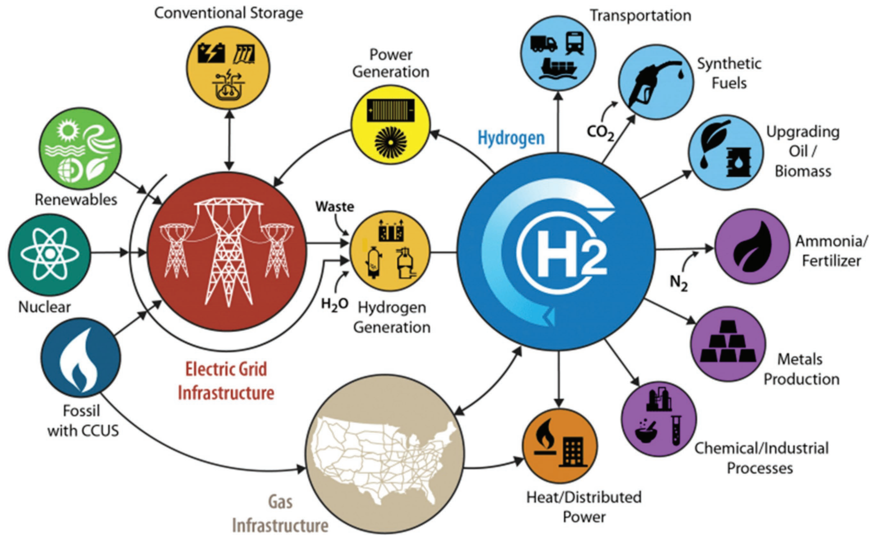

FIGURE 10.2 DOE's H2@Scale initiative to enable decarbonization across sectors using clean hydrogen.

Source: US DOE (2023).

In addition, clear targets have been set for each focus area. For example, the Earthshot challenge aims to reduce the production cost of clean hydrogen (green or blue) to $1/kg by 2031 and the infrastructure and storage cost to $2/kg (US DOE 2021a).

H2@Scale plans to achieve these targets by defining program drives and activities and executing them via regular workshops as well as providing grants and drawing on information from academia and the private sector. Funding for research and technology transfers is available to universities, national laboratories, and the private sector through cooperative research and development (R&D) agreements under public–private partnerships. Since the program's inception, over 20 H2@Scale R&D projects between national laboratories and industry partners have been established in areas such as the grid integration of electrolysis, development of fueling technologies and methods, and analysis of hybrid energy systems. The program also ensures coordination and collaboration internally, between the federal government and states, between the public and private sectors, and with international counterparts. Selected H2@Scale projects are likely to require supplemental investment in the form of cost-sharing with the private sector to adequately test and deploy new technologies.

National hydrogen policy in the United States was boosted by the Infrastructure Investment and Jobs Act (IIJA) signed into law by President Biden on November 15, 2021. The Act has earmarked $9.5 billion for the following clean hydrogen programs within the DOE:

- $8 billion for the Regional Clean Hydrogen Hubs Program to develop at least four large hydrogen hubs
- $1 billion for the Clean Hydrogen Electrolysis Program for the demonstration, commercialization, and deployment of green hydrogen projects
- $0.5 billion for the Clean Hydrogen Manufacturing and Recycling Program to support the clean hydrogen supply chain in the United States

The Act complements H2@Scale by boosting clean hydrogen R&D. It defines 'clean hydrogen' as hydrogen produced with a carbon intensity, at the facility, of 2 kg of CO_2 equivalent or less per kilogram of hydrogen produced (US Congress 2021). In addition, the Regional Clean Hydrogen Hubs program requires hubs to demonstrate feedstock diversity including from fossil fuels, renewable energy, and nuclear power.

In August 2022, President Biden signed the landmark Inflation Reduction Act (IRA). This may prove to be the single most important event in the history of clean hydrogen to date and a turning point for the nascent industry within and beyond the United States (Collins 2022). The IRA includes a section on hydrogen, including the provision of generous tax credits of up to $3/kg for 10 years that could make clean hydrogen produced in the United States extremely competitive (Table 10.1).

The IRA introduces a production tax credit (PTC) and extends the existing investment tax credit (ITC) to cover a proportion of the upfront costs of hydrogen projects, including that of standalone hydrogen storage technology (Cooper, Fleming, and Perlman 2022).

The eligibility criteria for the PTC are based on the emission intensity of the facility and are technology-neutral. Any hydrogen production facility can qualify for the PTC for a 10-year period beginning from the date of service. However, its lifecycle GHG emissions (well-to-plant gate) must not exceed 4 kg of CO_2 equivalent per kg of hydrogen. The base PTC amount under the IRA is set at $0.60/kg of hydrogen, as shown in Table 10.1. However, this can increase to a maximum of $3/kg of hydrogen if two conditions are met. First, the emission intensity for manufacturing hydrogen must fall between 0 and 0.45 kg of CO_2 equivalent per kg of hydrogen. Second, the project must comply with the prevailing wages and apprenticeship labor requirements (Samji et al. 2022).

TABLE 10.1 PTC for hydrogen producers under the IRA

Emissions intensity (kg of CO_2 equivalent per kg of hydrogen)	*Tax credit eligibility*	*Credit per kg of hydrogen*	*Qualifying facilities multiplier (5×)*
2.5 to 4	20%	$0.12	$0.16
1.5 to 2.5	25%	$0.15	$0.75
0.45 to 1.5	33.4%	$0.20	$1.00
Less than 0.45	100%	$0.60	$3.00

Source: Hydrogen Forward (2022).

A hydrogen facility with an emission factor of 0.45–1.5 kg of CO_2 equivalent per kg of hydrogen will only receive 33.4% of the \$0.60 base tax credit (\$0.20) if the wages and apprenticeship labor requirements are not met. However, if this condition is met, the eligible tax credit is multiplied by 5, resulting in a total of \$1/kg of hydrogen.[1] Alternatively, the facility owner can opt for the ITC instead of the PTC. Under the ITC, a tax credit of up to 6% can be received, which can rise to 30% if the labor and wage requirements are met (Samji, et al. 2022). However, the owner can also receive a separate 30% ITC for energy storage technologies, hydrogen included, if constructed before January 1, 2025.

This game-changing effort by the Biden Administration is starting to encourage other countries wanting to become major players in the nascent hydrogen space to speed the implementation of regulatory frameworks and incentives to deploy clean hydrogen production (see Chapter 8).

California strategy

California's motivations to establish a hydrogen economy are primarily driven by its challenging decarbonization targets (i.e., reduce emissions by 40% by 2030 and reach carbon neutrality by 2045) as well as its goals of producing 100% carbon-free electricity and reducing criteria pollutants (CA Legislative Information 2006, 2018a, 2018b, 2021). Its strategy has emphasized decarbonizing transportation with technology-agnostic policies to increase the adoption of zero-emission vehicles and a complementary effort to provide state funding for hydrogen-refueling stations (CA Legislative Information 2013, 2020a, 2020b; California Air Resources Board 2019, 2020, 2021a; New York Times 2020).

Hydrogen has long been part of the state's energy strategy, with the Hydrogen Blueprint Plan, which appeared as early as 2004, aiming to ensure hydrogen refueling stations can meet projected demand (California Matters 2020). An Executive Order in 2020 provided further impetus by targeting 100% of new vehicle sales to be zero-emissions vehicles by 2035 (CA Legislative Information 2020a). The vast majority of hydrogen consumption in California is gray hydrogen (~2 million metric tons/year), predominantly for refining. Green hydrogen demand in California is estimated to reach 4 million metric tons/year by 2050, equivalent to 15% of primary energy (California Energy Commission 2020). Producers of low-carbon hydrogen are eligible for Low Carbon Fuel Standard (LCFS) credits if their product benefits the transportation market. However, between 2016 and 2021, the spot market pricing for LCFS credits ranged from \$65 to \$200 per credit (California Air Resources Board 2021a). Therefore, a major challenge facing potential hydrogen developers in the state is that the variance in future LCFS prices results in highly uncertain project finances, leaving investors reluctant to commit.

Other major concerns and challenges in California include the uncertain rate of growth in demand for hydrogen, high renewable electricity costs for green production pathways, limited biomethane for renewable steam methane reforming (SMR) pathways, and onerous permitting processes (California Energy Commission 2020a). Addressing these challenges will require a combination of technology innovation, policy measures, financial incentives, and regulatory frameworks. To date, growth along the hydrogen value chain has been enabled by the state's rigorous policy framework, focusing on decarbonizing transportation. However, realizing the full potential of hydrogen will require sector coupling, namely, the interconnection of energy-consuming sectors (construction, transportation, industrial) with the power-producing sector. Policies must be designed to incentivize utilities to use hydrogen for the seasonal storage of renewable electricity and for industrial applications such as the production of steel and cement to reduce CO_2 emissions. The cost-effectiveness of hydrogen will improve greatly by formulating federal and state-level incentives that enable regional hubs with a variety of end uses.

Other state-level strategies

Following the example set by California, several other states have incentivized hydrogen use in the transportation sector. According to the American Legislative Exchange Council (2020) and Alternative Fuels Data Center (2021), which both track states' policies for hydrogen vehicles, 14 states have introduced bills related to hydrogen fuel cells since 2019. Bills fall into the following categories: procurement (CT, HI, MA, MD, NH, NY, OR), mandates (HI), incentives (CA, CO, CT, IL, HI, MA, NJ, TX, VA, WA), and infrastructure (HI, MA, VA, WA). Eleven of 26 bills have already been passed. States have also been supporting alternative fuel vehicles through a combination of laws and regulations and incentives. For example, Colorado and Washington provide consumers with incentives to purchase hydrogen fuel cell electric vehicles (FCEVs), and Hawaii offers benefits for FCEVs such as parking fee exemptions and high occupancy vehicle lane use.

Potential for US hydrogen exports

The United States has the potential to be a major player in the international hydrogen market, with a current hydrogen production of 10 million tons/year and the ability to produce large quantities of relatively cheap hydrogen from its abundant natural gas and renewable energy resources. The incentives under the IIJA and the IRA give a major boost to hydrogen producers in the United States, making the price of clean hydrogen highly attractive. There is an opportunity for potential hydrogen hubs on the Gulf Coast, as well in the East and West Coasts to be major exporting regions of hydrogen or ammonia, particularly to fast-growing markets in Japan and the European Union. Figure 10.3 shows how competitive US clean hydrogen exports to Germany can be with the inclusion of the PTC under the IRA.

However, to take advantage of this opportunity, more guidance is needed on the methodology for measuring GHG emissions and on how renewable energy is used (e.g., concept of additionality). The United States also needs to move quickly

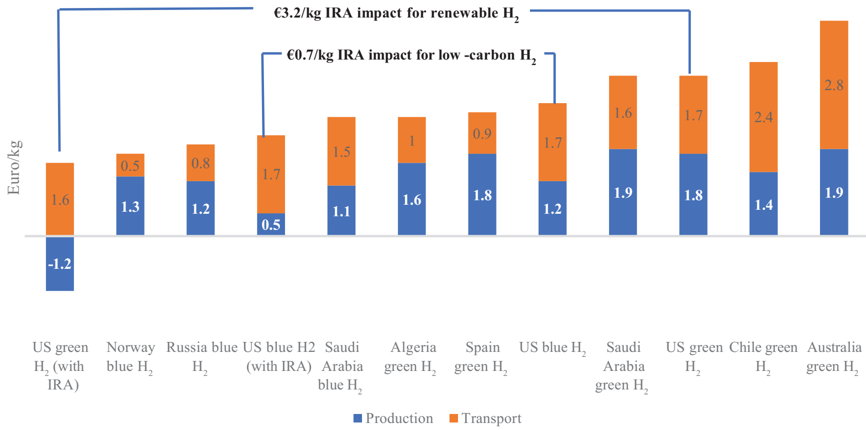

FIGURE 10.3 Landed cost of hydrogen in Germany as an end-product 2030, Euro/kg.

Source: Wilson (2022).

to leverage its competitive advantage, as Chile, the Middle Eastern countries, and Australia are developing export strategies and agreeing contracts to provide clean hydrogen to Japan and the European Union. In addition to policy incentives, the federal government must establish international trade relationships and smooth out the permitting process to hydrogen developers and exporters.

One factor that may determine the degree of exports is the local demand for hydrogen, for both existing and new use cases. As shown by the strategy, the United States aims to reach 50 million tons of clean hydrogen consumption by 2050 (from 10 million tons of unabated hydrogen today) to meet its national targets. Nonetheless, there is a clear opportunity for the United States to be a dominant competitor in the global hydrogen market, but the guidance and transparency on the GHG accounting and the consumption of clean electricity will need further clarification and whether they conform to the standards and regulations of the target markets.

Utilization of carbon-free hydrogen in the United States

Low-carbon projects

In the private sector, a number of low- and zero-carbon hydrogen projects are underway or in various stages of permitting and construction. These projects fall into four categories: producing blue hydrogen under SMR with CCS, building green hydrogen plants for electrolysis or gasification, retrofitting existing power plants to use some percentage of hydrogen blended with natural gas, and blending hydrogen into existing natural gas pipeline distribution systems.

North American blue hydrogen projects are leading the way. Five blue hydrogen facilities are operating in the United States and Canada, with three more under construction (Columbia Center for Global Energy Policy 2020). In the short-to-medium term, the abundance and low cost of natural gas in the United States means that blue hydrogen is currently cheaper than green hydrogen ($1–3/kg vs. $5–8/kg; US DOE 2020a). The addition of CCS to a steam methane reformer adds only $0.21/kg to the cost of the hydrogen if the CO_2 can be stored close to the production site (US DOE 2020a). However, blue hydrogen projects will also need to compete on emissions as the degree of incentives is correlated with carbon intensities.

Although 40 million tons of CO_2 are sequestered annually worldwide under CCS, significant challenges remain. First, CO_2 may be stored in either depleted oil and gas reservoirs or saline aquifers. Saline aquifers are widespread across the United States and often the closest storage option to avoid expensive CO_2 transport. However, in contrast to depleted oil and gas reservoirs, there is a limited amount of subsurface characterization and a lack of data to fully understand how a CO_2 plume might travel through the saline aquifer. Further, without pressure depletion from production, there is a possibility of triggering earthquakes. To mitigate these risks, meet regulatory requirements, and ensure social acceptance, data from characterization wells and seismic surveys must be collected and analyzed. This will take time and slow the development of blue hydrogen projects nationally.

Further, the cost of blue hydrogen remains higher than that of other fuels such as natural gas. However, policy incentives such as California's LCFS in conjunction with the federal carbon sequestration tax credit (45Q) or the clean hydrogen PTCs (45V) can improve the viability of producing blue hydrogen. Indeed, a recent report found that hydrogen generation with CCS in California is a profitable business venture (EFI and Stanford 2020). With LCFS credits of $100/ton of CO_2 layered on top of the previous 45Q credit of $50/tonne of CO_2, the resulting profit margin is $25–50/ton of CO_2 (equivalent to ~$5 per kilogram of hydrogen produced). The incentive for permanently stored CO_2 under the 45Q has been upgraded to $85/ton under the IRA which further enhances the profit margins.

Figure 10.4 shows a map of electrolyzers over 120 kW (~0.1 tons/day) and those under construction in the United States. To date, most installations have been on the East Coast and West Coast, and hydrogen is mostly used for transportation. However, some electrolyzer projects in the midwestern states have generated hydrogen for fertilizer production.

Table 10.2 lists selected green hydrogen plant projects ranging in scale and scope from small demonstration projects producing a few tons of hydrogen per day to large commercial plants generating more than 30 tons per day. Of these, the $1.9 billion Intermountain Power Project (IPP) in Utah is developing a commercial hydrogen hub. The project aims to retire existing coal-fired power plants and install 840 MW of new gas-fired electricity generation units by 2025. These units will initially use a blend of natural gas and 30% green hydrogen, with the plan to transition to 100% hydrogen by 2045 pending technological advancement. An on-site electrolyzer will provide green hydrogen. The IPP is also located close to natural

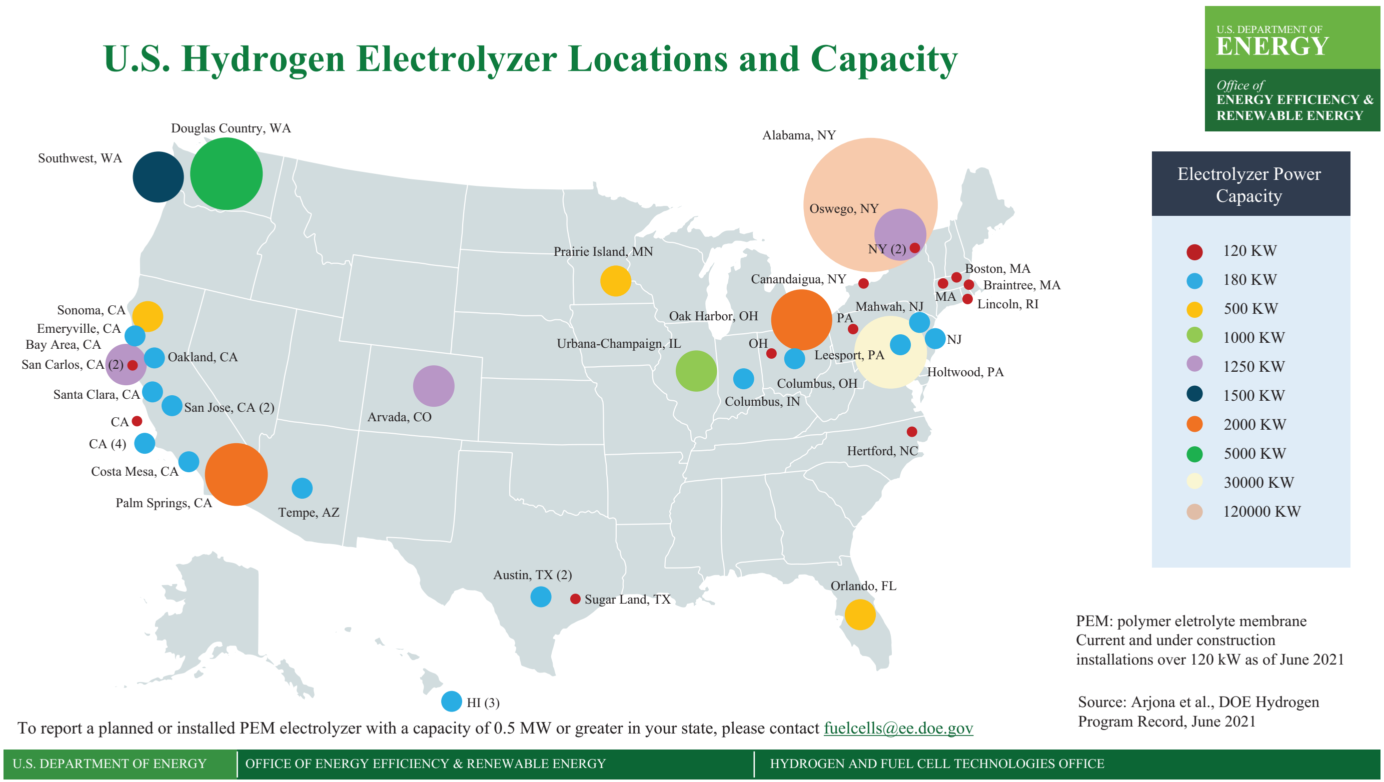

FIGURE 10.4 Map of US electrolyzer locations and capacities.

Source: US DOE (2021).

TABLE 10.2 Selected green hydrogen projects in the United States

Project	*State*	*Hydrogen production capacity (tons/day)*	*Hydrogen production process*	*Hydrogen use*	*Estimated operational commencement*
SGH2 Lancaster	CA	11	Gasification of biomass from landfill	Buildings/vehicles	2022
Fresno County (Plug Power)	CA	30	Solar electrolysis	Vehicles	2025
Florida Power and Light (Nextera)	FL	10	Solar electrolysis	Blend into a 23-MW natural gas power plant	2023
Camden (Plug Power)	GA	15	Solar electrolysis	Fuel cell vehicles	2022
New Jersey Resources (Howell)	NJ	0.065	Solar electrolysis	Demonstration: blend into the gas distribution system	2021
Atlantic Shores	NJ	2–4 (calculated)	Wind electrolysis	Pilot project (5–10 MW)	2028
Lancaster County	PA	15	Hydroelectric	Fuel cell vehicles	2022
Apex Clean Energy	TX	30	Wind electrolysis	Fuel cell vehicles	2025
IPP	UT	Not stated	Solar and wind electrolysis	840-MW coal power plant upgrade to run on a 30% hydrogen– natural gas blend	2025 (30%) 2045 (100%)
Douglas County Public Utility District	WA	2 (calculated)	Hydroelectric	Fuel cell vehicles	2021

Source: Compiled from press releases. A conversion factor of 48 KWh/kg hydrogen is used to calculate the volumes of generated hydrogen when no data are available.

salt domes where hydrogen can be stored. The power generated by the IPP will be used to power approximately 700,000 homes in southern California.

Another major project is the Advanced Clean Energy Storage project run jointly by Mitsubishi Hitachi Power Systems and Magnum Development, which plans to store up to 1,000 MW of hydrogen for seasonal energy storage (Magnum Development 2019). Similarly, the Wyoming Energy Authority has approved three feasibility studies: (1) evaluating a natural gas generator fed with blue and green hydrogen from solar electrolysis, (2) evaluating water access and compatibility to support green hydrogen production; and (3) planning biomethanation (i.e., the gasification of organic waste).

In addition to generation projects, combined cycle cogeneration power plants have announced upgrades to run on a percentage of hydrogen blended with natural gas, with a transition to 100% hydrogen when advances are made in turbine technology (Table 10.3). The first of these projects is the Long Ridge Energy Terminal in Ohio that began providing low-carbon power to customers in late 2021.

Finally, a handful of proposals have been submitted by utilities such as Southern California Gas, San Diego Gas and Electric, Southern Company, and Dominion Energy to blend various amounts of hydrogen (5%–20%) into existing natural gas pipelines. Efforts are already underway to address safety concerns about pipeline embrittlement and establish blending standards and guidance. The timeline for when utilities will actively begin injecting hydrogen into the pipeline is unclear.

The United States and Saudi Arabia: from fossil fuels to green hydrogen

Both the United States and Saudi Arabia are poised to become major players in low-carbon hydrogen. In April 2021, they both joined a newly established Net Zero Producers Forum along with Qatar, Canada, and Norway, countries that together represent about 40% of global oil and gas production. The forum will act as a platform for these countries to discuss pathways to decarbonization to reach net-zero emissions (US DOE 2021d). Leveraging such multilateral agreements and building on existing bilateral relationships are key drivers for both the United States and Saudi Arabia to accelerate their emissions reductions. Both countries have similar low-cost resource bases that can support the scale up of low-carbon technologies such as renewable power generation, carbon capture and storage (CCS), and hydrogen. For them to meet their ambitious blue hydrogen goals, it is critical for CO_2 storage to support the development of CCS projects (Zakkour and Heidug 2019).

The vast majority of global CO_2 storage facilities are in the United States (Global CCS Institute 2021) because of the benefits of the 45Q tax credit and California's LCFS. This fact demonstrates that when policy creates a business case for investment, projects proceed. Saudi Aramco has CCS experience, and it is involved in multiple projects that inject captured CO_2 to both store CO_2 and enhance oil recovery. However, further incentives, either at the national or at global levels (e.g.,

TABLE 10.3 Selected power plant upgrade projects in the United States

Company/facility	*State*	*Power plant capacity*	*Hydrogen use*	*Estimated operational commencement*
JERA Americas (Linden)	NJ	972 MW	Blending 40% hydrogen with natural gas in cogeneration units with six gas turbines (172 MW)	2022
NRG (Astoria, Queens)	NY	646 MW	Converting a peaker gas plant into a 437-MW hydrogen base plant	2040
Danskammer (River Road)	NY	530 MW	Converting a peaker gas plant into a hydrogen base plant	2030 (30% hydrogen) 2040 (100% hydrogen)
Cricket Valley Energy Center (Dover Plains)	NY	1.1 GW	Pilot project: blending 5% hydrogen into one of three cogeneration gas turbines	2022
Long Ridge Energy Generation Project (New Fortress)	OH	485 MW	Converting a gas power plant into hydrogen	2021 (15%–20%) 2030 (100%)
Emberclear (Harrison)	OH	1 GW	Converting a gas power plant into hydrogen	2023
Entergy (Sabine)	TX	1.2 GW	Building a new plant to run on a 30% hydrogen–natural gas blend	2026
IPP	UT	840 MW	Upgrading a coal power plant to run on a 30% hydrogen–natural gas blend	2025
Balico	VA	1.65 GW	Upgrading a natural gas power plant to run on a 30% hydrogen blend	Not stated

Source: Compiled from press releases.

Article 6 of the Paris Agreement) are necessary to advance CCS and overcome the economic hurdles in the Kingdom and globally. With the exception of the United States and EU nations, most countries have limited regulations and policy incentives to price CO_2 emissions and therefore scale up low-carbon projects.

The United States focuses on producing hydrogen to use domestically to reduce emissions and ensure both energy sustainability and energy security. Saudi Arabia, by contrast, has a smaller domestic market and focuses on producing hydrogen for export. Another contrast between the nations is that the United States has been establishing renewables capacity for decades, with renewables contributing 20% of its 1.2 million MW of electricity generation capacity (IEA 2020). On the contrary, Saudi Arabia has a relatively low renewable energy capacity installed nationwide and must scale this up drastically to build a dedicated hydrogen production facility (Braun and Shabaneh 2021). Moreover, the Kingdom is planning to meet half of its power needs from renewables by 2030 and has several projects underway.

US hydrogen policies have focused on developing markets, particularly transportation. However, with several federal proposals pending, future policies are likely to shift toward supply incentives such as the PTC and ITC. Saudi Arabia, as an early participant in the low-carbon hydrogen trading market, is likely to be influential in developing demand-side incentives such as the standardized certification of clean hydrogen. This could favor the Kingdom's hydrogen production technologies. The green certification of hydrogen, much like efforts being developed for natural gas, is likely to be based on lifecycle greenhouse gas emissions and could facilitate international trade in clean hydrogen.

Another difference is that the United States is a member of the Hydrogen Production Analysis Task Force within the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). The IPHE is developing a technical and analytical methodology for measuring lifecycle GHG emissions for hydrogen production (IPHE 2021). Although Saudi Arabia is not a member of this international partnership, it is aiming to develop an export hydrogen business, and thus more international cooperation on certification is expected. In addition, both countries can leverage the increasing R&D in hydrogen technologies and industrial processes being conducted by Mission Innovation, the intergovernmental organization to which both the United States and Saudi Arabia belong as members. Mission Innovation is a global initiative to invest in R&D and demonstration to make clean energy affordable by 2030.

Potential of hydrogen for decarbonization in the United States

Demand for hydrogen has been comprehensively studied at the federal level, through industry-led consortia, and in California. This work has been based on assessing the economic potential and cost parity of hydrogen relative to alternative fuel sources (ANL 2020; APEP 2020; California Energy Commission 2020a; Fuel Cell and Hydrogen Energy Association 2020; US DOE 2020b). The DOE's national laboratories have estimated the serviceable potential (potential for hydrogen demand at zero cost) as 106 million metric tons/year by 2050, whereas the economic potential (at threshold prices) is 22–41 million metric tons/year (NREL 2020). Drivers of decarbonization and policy will thus impact the economic potential of green hydrogen and determine which sectors are the earliest adopters.

As shown in Table 10.4, potential demand for green hydrogen could be at least five times greater than current market demand by 2050 if hydrogen can be supplied at $1/kg. The size of the market that ultimately materializes will depend on many

TABLE 10.4 Potential demand for (green) hydrogen by 2050

Willingness to pay ($/kg)	*Sector*	*Demand (million metric tons)*	*Cumulative demand (million metric tons)*	*Current sector CO_2 emissions (million metric tons)*
Assumed to be inelastic	Petroleum refining	7.5	7.5	36.2
Assumed to be inelastic	Biofuels	8.7	17.2	N/A
2	Ammonia	3.6	20.8	13.5
5	Light-duty vehicles	11.7	32.5	1106
5	Mid- and heavy-duty vehicles	5.2	37.7	716
<$1/kg	Synthetic methanol	14	51.7	N/A
0.8–1	Steel	12	63.7	42.6

Source: ANL (2020), EPA (2020), and Zang et al. (2021).

factors such as decarbonization policies and R&D. Early adopters of hydrogen may be those sectors that have fewer alternatives to decarbonize, such as transportation and biofuels.

Table 10.4 also provides details of the CO_2 emissions for the targeted sectors. Transportation has the highest emissions, followed by steel, petroleum refining, and ammonia (EPA 2020). Given that CO_2 emissions in the transportation sector are higher by some orders of magnitude, it makes sense to focus on transportation first. This approach also aligns with the projected cost trajectory (see the Case Study section for a discussion of the hydrogen transportation market in California). Steel has a high carbon footprint owing to fuel combustion and carbon in feed materials. While this has traditionally been an extremely difficult sector to decarbonize, hydrogen could be used as a heat-producing fuel and a clean-reducing agent.

In California, based on representative costs of renewable hydrogen substitutes and decarbonization drivers, many applications (e.g., transportation, refining, fertilizer, storage) become cost-competitive at a hydrogen production cost of $2–4/kg. This is followed by others (e.g., industrial, commercial, residential, thermal, and process heating) at $3–6/kg (APEP 2020; California Energy Commission 2020). Based on projected cost targets of $6/kg and $4/kg delivered by 2030 and 2050, respectively, demand for green hydrogen in California is expected to increase from virtually zero today to 0.4 million metric tons/year by 2030. Demand will rise further to up to 4 million metric tons/year by 2050. Green hydrogen will be used by road vehicles, thermal and process heating, generation and storage, refining, and ammonia (California Energy Commission 2020).

One approach that might enable the United States to reach the maximum potential demand scenario is employing a two-stage strategy framework, similar to that implemented in California (California Energy Commission 2020). In the first phase, during 2020–2030, focus should be placed on enabling deployment in industries (e.g., petroleum refining, biofuels, ammonia) that already exploit green and blue hydrogen using the following measures (ANL 2020):

(D1) **Fix long-term decarbonization targets** along with the corresponding pathways to create demand. This would require green (or blue) hydrogen to represent a certain percentage of all the hydrogen used. This approach is similar to the renewable portfolio standards in the electricity sector (Berry and Jaccard 2001) and biofuel blending standards in the automotive sector (Sorda, Banse, and Kemfert 2010).

(D2) **Enable regulation to remove barriers to hydrogen deployment**. This would require addressing regulatory barriers by, for example, developing standardized, risk-based guidance on limits for hydrogen blending in gas networks. These limits would need to account for the impacts of hydrogen on infrastructure materials and components (e.g., compressors) as well as end-use applications.

(D3) **Provide incentives (subsidies and tax credits) to ensure cost-competitiveness**. Given that green (or blue) hydrogen is more expensive than gray hydrogen, this would require incentives impacting capital, taxes, and/or operational costs of the order of $3/kg to become cost-competitive. For example, California's LCFS provides operational subsidies, whereas the national 45Q offers tax credits for carbon sequestration. Both these incentives are making blue hydrogen projects viable (EFI and Stanford 2020).

(D4) **Use risk-mitigation instruments to ensure private investment at scale**. This would entail developing financial instruments to reduce the risks to hydrogen development (e.g., long-term power purchase agreements for renewable power projects). By reducing both price and quantity uncertainties, investment risk decreases, eventually lowering both the cost of capital and delivered electricity cost. Similar techniques could be used to reduce the delivered cost of green (or blue) hydrogen.

In the second phase, during 2030–2040, as green hydrogen becomes competitive with other options (including gray hydrogen), deployment in hard-to-decarbonize industries (e.g., heavy-duty vehicles, shipping, aviation, steel, cement) should be fostered using similar measures (ANL 2020).

Research efforts to develop clean hydrogen technologies

In the United States, hydrogen research is primarily funded by the DOE in collaboration with the 17 national laboratories, many academic institutions, and the private sector. In the DOE, the Hydrogen and Fuel Cell Technologies Office spearheads the program with participation from the Offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy and Carbon Management (FECM), Nuclear Energy (NE), Science (SC), Electricity (OE), and the Advanced Research Projects Agency–Energy (ARPA-E). Over the last decade, DOE funding for hydrogen and

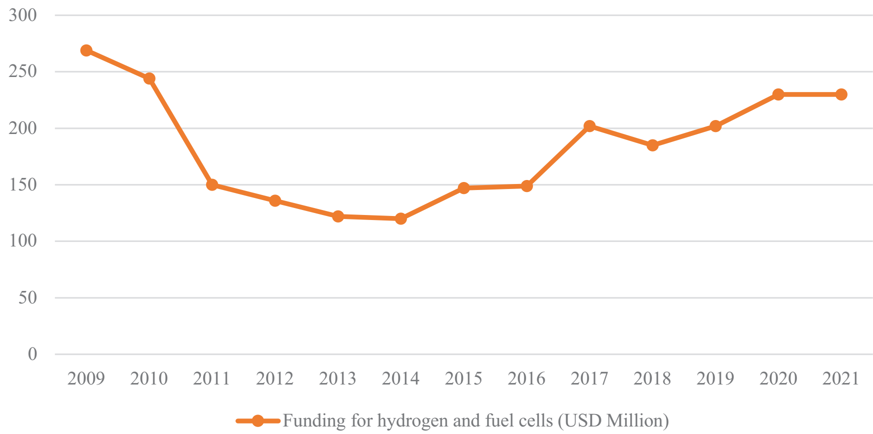

FIGURE 10.5 DOE funding for hydrogen and fuel cells.

Source: 2009–2019 data (US DOE 2009–2019), 2020 data (US DOE 2020c, with an estimate of $20 million for the ARPA-E), and 2021 data (US DOE 2021b, with estimates of $20 million for the ARPA-E, $11 million for the NE, and $19 million for the SC).

fuel cells has been $100–280 million (see Figure 10.5). About two-thirds has been allocated to projects within the EERE and the remainder divided between the other departments (FECM, NE, SC, OE, and ARPA-E) (US DOE 2009–2019). For context, in FY2020, the sustainable transportation division of the EERE allocated $150 million to hydrogen and fuel cell technology, $260 million to bioenergy technology, and $396 million to vehicle technologies, mostly electric vehicle development (ITIF 2020).

The federal budget reflects that the emphasis of hydrogen research in the United States is expanding from applications of fuel cells in light-duty vehicles to a stronger focus on integrated hydrogen systems at scale, in line with the H2@Scale program (see the green segment in Figure 10.6).

Fuel cells

Annual funding for fuel cell R&D (materials, components, systems) ranged from $32 million in 2018 to $25 million in 2021, as shown in Figure 10.6. The primary objectives of the fuel cell program are to reduce the cost and improve the durability of fuel cells through the development of catalysts and membranes to allow them to compete with alternative technologies. In 2019, this program developed targets for heavy-duty vehicles. These targets were to reduce the cost of the fuel cell system from ~$190/kW to $60/kW by 2050 and increase operational hours from 20,000 to 30,000 hours (US DOE 2019c). Workshops on other applications such as rail, marine, and aviation were held in 2019 and 2020 to help inform and develop research

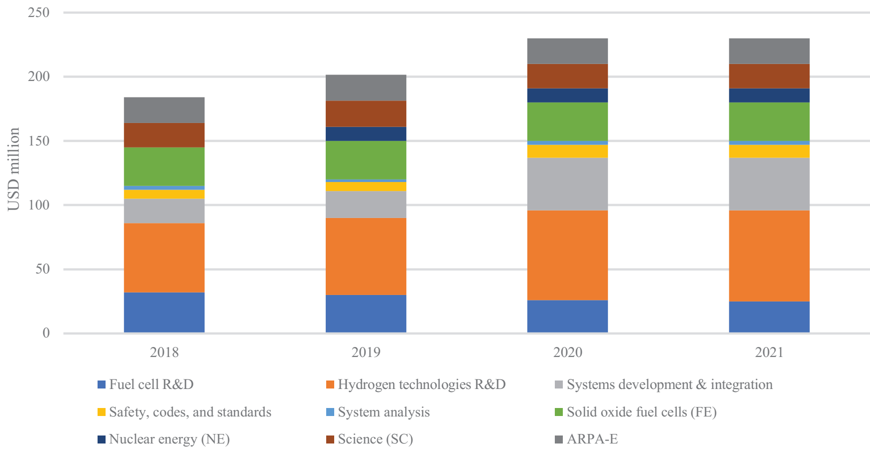

FIGURE 10.6 Emphasis of hydrogen research in the United States.

Source: 2018–2020 data (US DOE 2020c, with an estimate of $20 million for the ARPA-E) and 2021 data (US DOE 2021b, with estimates of $20 million for the ARPA-E, $11 million for the NE, and $19 million for the SC).

targets. In addition to transportation, the fuel cell program continues to research stationary applications including distributed power generation and combined heat and power for residential and commercial settings.

Unlike conventional fuel cells that use hydrogen as the input, solid oxide fuel cells use hydrocarbon fuels such as natural gas as the input and oxidize the gas at very high temperatures. Solid oxide fuel cells offer the advantage of having high combined heat and power efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. The development of low-cost materials with high durability at high operating temperatures is the key technical challenge facing this technology. The FECM's solid oxide fuel cell program has an annual budget of $30 million. Stationary fuel cell targets include reducing the system cost from ~$2000/kW to $900/kW with 40,000 hours of durability.

Hydrogen production, storage, and infrastructure

To improve the overall value proposition of hydrogen relative to existing fuels, the efficiency of the system must be improved and the costs throughout the value chain, from hydrogen generation to the storage and distribution of the molecules, must be reduced. DOE funding for these research areas increased from $54 million in 2018 to $71 million in 2021. The cost of generating hydrogen is fundamentally related to the cost of the input fuel (typically natural gas or renewable electricity) as well as the capital and operating expenses of the facility.

Beyond fossil-fuel-derived processes such as SMR, electrolysis (water splitting) is an alternative technology being deployed commercially that now produces about

1% of hydrogen in the United States (US DOE 2020a). Despite this low proportion, a significant research portfolio of alternative hydrogen production technologies already exists at various stages of technological readiness. The primary research target is to reduce the costs of green methods such as electrolysis (at high and low temperatures), photoelectrochemistry, solar thermal chemistry, and biomass/biological processes. The potential cost of current green hydrogen generation technologies in the United States is \$5–6/kg and the DOE target is \$1–2/kg (US DOE 2020b). The goal is to reduce the capital cost of an electrolyzer from as much as \$1,500/kW to \$300/kW with 80,000 hours of durability at 65% system efficiency by 2030 (US DOE 2020d).

HydroGEN is a consortium of six national laboratories, led by the National Renewable Energy Laboratory, which aims to accelerate the R&D and demonstration of advanced water-splitting technologies. In 2019, it added 11 new projects and continued to support another 20 existing projects related to hydrogen generation. Both DOE projects and private companies such as Nel Hydrogen are focusing on reducing the capital costs of electrolyzers, while improving their performance and durability.

In addition to the cost and performance of the electrolyzer itself, a large proportion of the green hydrogen cost is associated with the cost of renewable electricity. Until low-cost renewable electricity is available at a higher capacity factor throughout the United States, blue hydrogen offers a potential solution to develop the hydrogen market sooner. The fundamentals of blue hydrogen (i.e., SMR and CCS technologies) are well understood. However, research is necessary to develop more efficient conversion processes, capture a higher percentage of CO_2 (the most is about 90%), fully understand how the CO_2 travels and interacts with the subsurface, and develop associated hydrogen storage technologies (US DOE 2021c). In addition, several novel pathways exist such as the SMR of renewable natural gas collected from dairies and landfills. In Nevada, for example, Air Liquide is building a \$150-million plant that will use renewable natural gas in part to produce 30 tons of liquid hydrogen per day.

The thermocatalytic decomposition of methane, also known as methane pyrolysis, is another route to producing hydrogen from natural gas while mitigating the production of CO_2 through the production of solid carbon coproducts such as carbon black. Methane pyrolysis is in an early stage of R&D, with only one commercial plant in operation (Monolith Materials; Palo Alto Research Center 2022). Nonetheless, the technology could be economically viable when the carbon price exceeds \$21/ton of CO_2 equivalent depending on the product carbon sales (Parkinson et al. 2018; Riley et al. 2021). Moreover, of the companies that have initiated biomass gasification projects to generate hydrogen from waste products, the most notable is the world's largest green renewable hydrogen facility being launched by SGH2 in California. This facility processes 40,000 tons of recyclable solid waste annually and produces 11,000 kg of hydrogen per day. This project will save the city of Lancaster \$50–75/ton annually in avoided landfill costs.

However, there are considerable challenges. For example, storing and transporting hydrogen is inherently difficult because hydrogen has such a low density that it requires significant compression, while hydrogen molecules are very small and can diffuse through metals, creating embrittlement. R&D in the area of hydrogen storage is aiming to reduce the cost of both stationary storage technologies and onboard vehicles. It will do so by using compressed gaseous hydrogen, low-cost liquefaction, liquid and cryogenic hydrogen in stationary tanks, tube trailers/pipelines, materials-based storage, and chemical hydrogen carriers. The DOE onboard targets are to increase usable specific-energy from 1.5 kWh/kg of hydrogen to 2.2 kWh/kg and decrease the overall hydrogen storage system cost (including materials, tanks, balance of plant) from $10/kWh to $8/kWh (US DOE 2020e). Research on solid-state hydrogen storage materials is already underway by the Hydrogen Materials Advanced Research Consortium.

On the critical issue of how to distribute hydrogen regionally, the Hydrogen Materials Compatibility Consortium is researching how hydrogen affects polymers and metals across applications such as refueling stations, storage tanks, pipelines, and compressor components.[2] In 2021, its labs participated in a multi-lab project aiming to overcome the technical barriers to hydrogen blending in natural gas pipelines, such as materials compatibility (US DOE 2022).

Systems development and integration

The US DOE funding for systems development and integration increased from $19 million in 2018 to $41 million in 2021 to improve the performance of hydrogen and fuel cell technologies in new sectors such as grid integration, heavy-duty transportation, energy storage, and industrial applications (e.g., steel and cement). Examples of large projects that have received such funding include the demonstration of hydrogen production and use onboard a floating barge in California, integration of hydrogen production with a nuclear power plant, creation of a workforce training program to develop skills for the hydrogen and fuel cell industry, and integration of a 1.5-MW fuel cell with a data center in Washington.

In Texas, H2@Scale is funding half of a $10.8 million project to demonstrate that renewable hydrogen can be an economically viable fuel for a broad range of end-use applications. The project, led by Frontier Energy in collaboration with the Gas Technology Institute and The University of Texas at Austin, has two goals (UT Austin 2020). First, in Austin, an integrated system is being built that incorporates hydrogen sourced both from electrolysis (powered by solar and wind) and from the SMR of renewable natural gas from a Texas landfill. The hydrogen will power a stationary fuel cell to provide clean reliable power for the Texas Advanced Computing Center. It will also supply a hydrogen refueling station to fill a fleet of Toyota Mirai FCEVs. Second, at the Port of Houston, the project team will assess the available resources, prospective hydrogen users, and delivery infrastructure (e.g., existing pipelines that supply hydrogen to refineries). The study will examine policies, regulations, and economics so that industry can develop a strategic action plan to develop heavy-duty fuel cell transportation and energy systems.

The H2@Scale project in Florida, which has a DOE budget of $9.1 million, will use hydrogen from solar-powered electrolysis to meet several end-use applications. These applications include providing residential and commercial backup power and refueling a fuel cell vehicle fleet. This project is led by Plug Power in partnership with the Orlando Public Utilities Commission. Florida is also the location of the $65-million NextEra Genesis pilot project, which aims to run a 20-MW electrolyzer on dedicated solar PV (Greentech Media 2020). Green hydrogen will be mixed into the feedstock at the 1.75 GW Okeechobee natural gas plant, thus lowering carbon emissions. The Hydrogen and Fuel Cell Technologies Office also funds R&D to advance hydrogen and fuel cells for medium- and heavy-duty trucks. This includes the provision of over $18 million to support projects addressing gaseous fuel storage; high-throughput fueling technologies; and high durability, low-platinum membrane electrode assemblies (US DOE 2019b).

Additional H2@Scale demonstration projects include the integration of low- and high-temperature electrolyzers at nuclear power plants to produce hydrogen for in-house supply and meet market demand nationally. On the first point, site selection is underway for a $7.2-million project led by Exelon. This project will aim to demonstrate low-temperature electrolyzer hydrogen generation for in-house supply at a nuclear power plant. On the second point, the DOE has provided $9 million to Energy Harbor to demonstrate hydrogen generation at the Davis–Besse nuclear power plant in Ohio to help meet the market demand from hydrogen consumers nationally.

Hydrogen research enablers

Although research in the United States is mostly funded at the federal level, state-level policies, renewable resources, and infrastructure needs vary greatly. Some aspects of hydrogen R&D and the launch of hydrogen technologies are likely to occur at the regional level and pave the way for applications nationally. Hence, dependable federal and state-level decarbonization targets that are technology-agnostic, combined with public incentives and safety standards, will enable hydrogen pilot projects and focus R&D efforts (Fuel Cell and Hydrogen Energy Association 2020).

To bring science and technology concepts to high technology readiness levels affordably, a supply policy framework is a useful counterpart to the recommended demand framework. This policy framework should enable the development of the required technologies such as CCS (for blue hydrogen) and electrolyzers (for green hydrogen) through the following five steps (US DOE 2020b):

- Identify focus areas (e.g., production, delivery, storage, conversion, apps)
- Set targets for these focus areas (e.g., generation costs of $2/kg by 2030 and $1/kg by 2050)
- Ensure the enabling infrastructure is in place (e.g., workshops, technology transfer)
- Provide financial support in the form of grants (R&D and demonstration) and loans (pilots)
- Enable risk mitigation (e.g., loan guarantees for pilots).

While the federal DOE hydrogen program includes all these framework steps, each state in the United States must develop a similar framework tailored to its individual needs. For example, in California, the generation cost targets may differ based on electricity costs.

Case study: the transport sector in California

California leads the nation and much of the world in formulating policies to mitigate climate change. The state has near-term goals of a 40% emissions reduction (relative to the 1990 baseline) and 60% renewable electricity by 2030; it has a long-term target of net-zero emissions by 2045. An Executive Order issued in September 2020 requires new passenger cars and trucks to be zero-emission types by 2035 and all medium- and heavy-duty vehicles to be zero-emission types by 2045 (Executive Department State of California 2020).

The zero-emission choices for road vehicles are essentially battery electric vehicles and hydrogen FCEVs. Battery electric vehicles account for around one-tenth of all new cars sold in California. Moreover, 7.5 million passenger plug-in electric vehicles are anticipated to be on its roads in 2030, which will require 1.2 million chargers to meet demand (California Energy Commission 2021). By contrast, FCEVs account for approximately 0.01% of passenger vehicles (California Fuel Cell Partnership 2020). However, the pace of FCEV adoption is following a similar trend to that of battery electric vehicles introduced in 2010, with the expectation of steep market growth over the next several years (California Air Resources Board 2020). Further, by 2020, the total operating costs of passenger battery electric vehicles were already $0.41/mile cheaper than those of FCEVs. If FCEVs do achieve high penetration rates and the hydrogen price at the pump decreases, FCEVs could be the cheaper option on a total cost of ownership basis by 2040 (Morrison, Stevens, and Joseck 2018). Indeed, some classes of FCEVs will reach cost parity with battery electric vehicles as soon as 2025 (e.g., regional trains, heavy- and medium-duty trucks, small ferries, and SUVs). Other classes will reach cost parity by 2030 (e.g., vans, short-distance urban buses, large ferries, mid-size short range vehicles, and aviation; Transport Environment 2020). To support the growing FCEV population and meet projected FCEV market growth, California has set hydrogen infrastructure targets.

For instance, Assembly Bill 8 allocates $20 million per year toward building hydrogen refueling stations until at least 100 stations are in operation.

The growth in the hydrogen transportation sector is primarily driven by the state's policy incentives. First, the California Air Resources Board's LCFS Hydrogen Refueling Infrastructure credit provision initiated the development of nine new stations in 2020 (California Fuel Cell Partnership 2020). Second, the California Energy Commission is cofunding new hydrogen fueling stations. These incentives are expected to help meet the goal of building 100 new stations if there are no development delays. However, the goal of building 200 new stations by 2025 will require further funding and incentives as well as streamlining the station construction and permitting process (Baronas and Achtelik 2019).

Existing refueling stations are primarily supplied with hydrogen generated by the SMR of natural gas. The affordability of natural gas makes SMR the most common and economical way to produce hydrogen. The median level of CO_2 emissions normalized for SMR hydrogen production is 9.3 kg of CO_2 per kilogram of net hydrogen produced (Sun and Elgowainy 2019). If the vision of 200 stations in California by 2025 is realized at an average dispensing rate of 1,500 kg of hydrogen per day, the corresponding emissions would be 1 million metric tons of CO_2/year. The three refueling stations in San Francisco owned by Shell are supplied with renewable hydrogen generated from biogas at the Air Liquide plant in Nevada. Nonetheless, California will need to further incentivize blue and green hydrogen generation pathways to realize the zero-emissions potential of hydrogen.

The real promise of hydrogen is in decarbonizing the heavy-duty sector. In particular, it offers major advantages over battery electric trucks and other large vehicles in terms of storage density, refueling time, and storage tank weight. For example, hydrogen fuel cells have a significantly higher energy storage density than lithium-ion batteries, which results in a longer range without sacrificing payload. An average FCEV heavy-duty truck requires about 50 kg of hydrogen to travel 750 miles, and the hydrogen tank system weighs about a quarter of the batteries that would be required to travel the same distance (Cunanan et al. 2021; Walker 2021). Additionally, FCEV refueling time is approximately 15 minutes compared with the eight hours required to fully charge a battery electric truck. While use in urban settings (e.g., refuse trucks) might allow overnight charging, short refueling times are important for regional trucking services.

The 'shore-to-store' project for the twin ports in Los Angeles and Long Beach (in collaboration with Toyota) is particularly noteworthy (Port of Los Angeles 2018). This project is building a fuel cell infrastructure (i.e., two refueling stations) to test how efficiently a heavy-duty FCEV trucking fleet can deliver cargo from the ports to the surrounding region. Return-to-base fleets such as those used in this project are widely anticipated to facilitate the early stages of the hydrogen refueling infrastructure necessary to expand the use of FCEVs.

In summary, California has demonstrated that state-level policy can drive the hydrogen transportation market. To fully leverage the decarbonizing potential of hydrogen in the heavy-duty sector, a robust inter-regional hydrogen network for transportation must be established. This will require federal and state-level policy to incentivize hydrogen use in transportation, akin to a national equivalent of the LCFS. It will also need large investment from the federal government and cooperation among states to build the necessary refueling infrastructure. Ultimately, in both the United States and overseas, the use of hydrogen for transportation and other applications must be driven by the central government to subsidize the higher cost of hydrogen relative to more carbon-intensive fuel alternatives.

Conclusion

Hydrogen is garnering considerable attention in the United States as a clean energy carrier. The current hydrogen production of 10 million tons/year, mostly for refining and agriculture, is expected to increase to more than 50 million tons/year by 2050. Going forward, hydrogen will be used to decarbonize the heavy industry, transportation, and power sectors. The United States is well positioned to make low-carbon hydrogen using solar- and wind-generated renewable electricity and its abundant natural gas resources coupled with CO_2 geologic storage. The incentives under the IRA and the IIJA will potentially make the United States one of the most competitive producers and exporters of clean hydrogen.

Over the last decade, the US DOE has maintained a strong hydrogen R&D program dedicated to reducing the cost of low-carbon hydrogen generation, fostering the storage and distribution of hydrogen, and developing specific applications such as fuel cells. However, focus is shifting toward enabling the demonstration of integrated hydrogen systems at scale. The DOE is also working with the private sector to develop hydrogen hubs, particularly at the major industrial centers and ports along the Gulf Coast and in California.

The United States and Saudi Arabia have both expressed a keen interest in developing a hydrogen economy and share many similarities in terms of their existing energy infrastructures, natural resources, and technical capabilities. However, while the United States is producing and using hydrogen domestically to support its decarbonization agenda, Saudi Arabia is expected to focus on remaining a low-cost and reliable energy exporter.

Notes

1 To receive the full credit, the owner of the facility is required to prove that all workers were paid the prevailing wages during the construction and repair of the project. The owner must also ensure that certified apprentices make up an applicable percentage of all labor hours (Samji et al. 2022). Guidance on the prevailing wages and apprenticeship labor had not been released by the Secretary of the Treasury at the time of writing.

2 The Hydrogen Materials Compatibility Consortium is led by Sandia National Laboratories and Pacific Northwest National Laboratory in collaboration with Oak Ridge National Laboratory, Savannah River National Laboratory, and Argonne National Laboratory.

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11

THE ROLE OF HYDROGEN IN AUSTRALIA'S DECARBONIZATION AND EXPORT STRATEGY

Bart Kolodziejczyk

Introduction

Australia is a major producer and exporter of raw materials in the Asia-Pacific region (International Trade Administration 2021). It is among the top five producers of most of the world's key mineral commodities as well as the world's largest exporter of black coal (by value), iron ore, alumina, lead, and zinc (Geoscience Australia 2021) and the second-largest exporter of uranium (Natural Resources Canada 2022). Australia is also one of the largest fossil fuel exporters in the region, shipping predominantly liquefied natural gas (LNG) and black coal. The Australian minerals sector accounts for 12% of gross domestic product (GDP) (Senior et al. 2022), with oil and gas exports adding an additional 3% of GDP (Battersby 2021).

Australia's raw materials export-oriented economy has proven to be profitable and scalable, delivering wealth to the nation. However, the exploited resources are finite and highly carbon intense. Hence, the federal government and major companies are seeking to establish a new export revenue stream using Australia's growing expertise in the renewable energy sector. Crucially, such a revenue stream must be more attuned to the requirements of a carbon-constrained world. Future industry will rely on the country's vast and infinite renewable energy resources such as wind and solar to produce clean fuels and commodities for exporting to nations that lack such abundant resources, including Japan, South Korea, and Singapore. Some Australian projects are looking even further by aiming to export green hydrogen and its derivatives to markets in Europe and North America.

Federal and state governments are supportive of this emerging industry. The majority of state governments have produced hydrogen roadmaps outlining the opportunities and challenges for deploying a hydrogen industry at scale. Similarly,

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the national hydrogen strategy looks beyond state boundaries to explore opportunities and synergies for hydrogen between Australian states and territories. Further, Australia's national research organization, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), has a long tradition of researching renewable energy and hydrogen and holds a vast intellectual property portfolio of hydrogen-related technologies. Further, several startups have emerged to produce hydrogen and ammonia, store and transport hydrogen, and encourage its end use, as discussed in the research section in more detail.

Australia is focused on decarbonizing industries such as mineral processing, fertilizer production, and oil and gas using locally produced hydrogen. It is a major ammonia producer in the Asia–Pacific region, producing 1,582,000 tons in 2018 (Coherent Market Insights 2020). Hence, Australian ammonia producers are looking at displacing existing gray hydrogen with its green counterpart to produce low-carbon ammonia. For example, Yara International is carrying out a feasibility study at its Pilbara plant to establish whether it can replace up to 30,000 tons of hydrogen produced using natural gas with green hydrogen from electrolysis. With annual production of 850,000 tons, Yara's Pilbara site alone accounts for approximately 5% of global ammonia production (Arenawire 2020). Local iron ore-mining companies are also exploring pathways to produce and use green hydrogen to produce sponge or pig iron using green hydrogen to displace natural gas in direct reduced iron plants or coke in blast furnaces, respectively.

The abovementioned factors position Australia as one of the leading green hydrogen exporters globally. This chapter analyzes its challenges and opportunities in the nascent global hydrogen market. Starting with Australia's hydrogen strategy, its opportunities to export low-carbon hydrogen and its derivatives are explored and domestic hydrogen use cases are presented. The research section explores the hydrogen R&D landscape and growing hydrogen startup ecosystem. The case study section discusses one of the most prominent blue hydrogen projects globally, and the conclusion section briefly explores the synergies and opportunities for collaboration between Australia and Saudi Arabia.

Strategy

Australia's hydrogen strategy is formulated by the national hydrogen strategy commissioned by the Australian Department of Industry, Innovation and Science (COAG Energy Council Hydrogen Working Group 2019). The document, released in November 2019, contains 57 strategic actions for the government, which revolve around several broad topics:

- Creating an adaptive pathway to clean hydrogen growth (four actions)
- Activating a large market (three actions)
- Coupling hubs and sectors (two actions)
- Assessing the needs of the hydrogen infrastructure (two actions)

- Supporting research, pilots, trials, and demonstrations throughout the supply chain (three actions)
- Using clean hydrogen in Australian gas networks (five actions)
- Taking initial steps toward using hydrogen for transport (seven actions)
- Enacting responsive regulation (three actions)
- Adopting shared principles to create nationally consistent regulations (one action)
- Implementing a coordinated approach to planning and regulatory approval for hydrogen projects (one action)
- Integrating hydrogen into energy markets (three actions)
- Understanding hydrogen's role in providing a secure and affordable energy supply (three actions)
- Creating certainty around taxation, excise, and other fees or levies for hydrogen (two actions)
- Forming bilateral partnerships to build markets (two actions)
- Creating a hydrogen certification system (four actions)
- Building community knowledge and engagement (two actions)
- Conducting responsible industry development (one action)
- Providing skills and training for the hydrogen economy (four actions)
- Providing hydrogen training for emergency services (one action)
- Providing hydrogen training for regulators (one action)
- Coordinating nationally (three actions)

Subsequently, Australian states, given their significant autonomy, have built on the national hydrogen strategy to generate their own tailored strategies and roadmaps that focus on the local conditions and opportunities (Table 11.1).

In Australia, the hydrogen strategy plays a major role in another government strategy document called the Low Emissions Technology Statement, initially published in 2020 (Government of Australia 2020) and updated in 2021 (Government of Australia 2021). The 2021 Low Emissions Technology Statement lists hydrogen along with six other priority technologies, namely, ultra-low-cost solar, energy storage, low-emission steel, low-emission aluminum, carbon capture and storage, and carbon capture in soil. The same document states that clean hydrogen could be produced in Australia for under A$2 (US$1.37) per kg by 2025. Some of these seven priority technologies listed in the Low Emissions Technology Statement 2021 are reliant on each other (Government of Australia 2021). For example, low-emission steel can be achieved through a hydrogen pathway. Hydrogen is also often listed as a viable pathway for large-scale long-duration energy storage, whereas carbon capture and storage is often considered by the Australian oil and gas industry as a possible pathway for low-emission hydrogen production. The world's first pilot project for producing hydrogen from brown coal, performing carbon capture and storage in underground caverns, and exporting the produced blue hydrogen to Japan is being run by Kawasaki Heavy Industries and other Japanese proponents in Victoria (Hydrogen Energy Supply Chain 2022).

TABLE 11.1 Hydrogen strategies and roadmaps by state

Document	*State or federal government*	*References*
Renewable Hydrogen Industry Development Plan	Victoria	(State of Victoria Department of Environment, Land, Water and Planning 2021)
South Australia's Hydrogen Action Plan	South Australia	(Government of South Australia 2019)
NSW Hydrogen Strategy	New South Wales	(New South Wales Government 2021)
Western Australian Renewable Hydrogen Strategy and Roadmap	Western Australia	(Western Australia Government 2020)
Queensland Hydrogen Industry Strategy 2019–2024	Queensland	(Queensland Government 2019)
Northern Territory Renewable Hydrogen Strategy	Northern Territory	(Northern Territory Government 2020)
National Hydrogen Strategy	Australian Department of Industry, Innovation and Science/Australian government	(COAG Energy Council Hydrogen Working Group 2019)
Low Emissions Technology Statement 2021	Australian government	(Government of Australia 2021)
National Hydrogen Roadmap	CSIRO	(Bruce et al. 2018)

Australia's hydrogen strategy has thus far centered on economic gains rather than climate change mitigation goals. Australia's industry is heavily reliant on carbon-intensive sectors, including mining and exporting LNG. Hence, while the national hydrogen strategy does commit to reducing carbon emissions to meet the country's Paris Agreement obligations, the main motivation for hydrogen production in Australia is the perceived opportunity to develop new export markets, diversify the export economy, create jobs, and attract local and foreign investment. Another motivation for Australia to become a first mover in hydrogen exporting is the potentially diminishing demand for fossil fuel exports, which might facilitate hydrogen production as a viable substitute.

Australia's hydrogen export strategy assumes a large offtake from Asian countries such as Japan, South Korea, and Singapore. Its proximity to Asian markets is a clear advantage since shipping hydrogen can cost significantly more than exporting hydrogen. This fact, together with the long history of energy exports and established relations with Asian customers through LNG exports, places Australia in a strong position compared with other emerging hydrogen exporters including Saudi Arabia. Although the potential competition between Australia and Saudi Arabia for hydrogen exports may benefit Asia and spur demand, large-scale hydrogen offtake does not exist and is highly uncertain, while the global market is highly competitive. The hydrogen export industry also assumes that low-carbon hydrogen can be produced at A$2–3 (US$1.37–2.05) per kg. Nonetheless, both Australia and Saudi Arabia have signed memorandums of understanding with Japan to explore potential export opportunities, while Saudi Arabia has entered into a similar agreement with South Korea (KBS World 2022, Ministers for the Department of Industry, Science and Resources 2022, S&P Global Commodity Insights 2021). Both countries are also actively pursuing hydrogen export opportunities to Germany (Department of Climate Change, Energy, the Environment and Water 2020, ICIS 2021).

While hydrogen has long been used as industrial gas derived from the decomposition of natural gas, green hydrogen has never been proven at scale. Australia's vision to become a major producer and potentially the first mover in global hydrogen production and export by 2030 is explained in the hydrogen roadmap. To achieve this vision, the Australian government, including the Australian Renewable Energy Agency (ARENA), is funding a broad range of hydrogen-related demonstration projects to prove the viability and scalability of the required technology. For example, in 2021, ARENA allocated A$103 million (US$70.9 million) to three projects proposed by Engie Renewables, ATCO Australia, and Australian Gas Networks to install 10 MW electrolyzer plants at sites in Western Australia and Victoria. At that time, the proposed electrolyzer plants were among the world's largest renewable hydrogen demonstrations (Arenawire 2021).

At the broad scale, Australia's national hydrogen strategy is aiming to develop a sustainable and vertically integrated industry, including supplying raw materials and manufacturing its own essential equipment. Enhanced grid connectivity and capacity as well as increased port availability for exports will be required to achieve this aim. Further, ARENA has introduced the Clean Hydrogen Industrial Hubs Program, which includes the provision of Hubs Implementation Grants (Table 11.2) and Hub Development and Design Grants (Table 11.3). Bell Bay (Tasmania), Darwin, the Eyre Peninsula (South Australia), Gladstone, Hunter Valley, Latrobe Valley, and Pilbara are the priority prospective hub locations based on the interest of industry and those location's existing capability, infrastructure, and local resources.

The funds allocated under the Hubs Implementation Grants reached A$430 million (US$296 million), while those under the Hub Development and Design Grants totaled A$23 million (US$18.8 million). Although the majority of these hubs are located in coastal areas with existing port facilities, other hubs are envisioned in areas with heavy industry to deploy green hydrogen in decarbonization efforts. For example, there is an opportunity to use green hydrogen as a clean reductant for iron ore processing and steelmaking. While the majority of Australia's raw resources have been exported for processing overseas, using green hydrogen in hard-to-abate industries is opening up new opportunities for local entities to process domestically produced mineral resources. Such local processing of mineral resources could

TABLE 11.2 Announced hydrogen hubs under ARENA's Clean Hydrogen Industrial Hubs Program: Hubs Implementation Grants

Proposed hub	*State*	*ARENA funding*
Western Australian Government's Pilbara Hydrogen Hub	Western Australia	Up to A$70 million (US48.2 million)
BP Australia's H2Kwinana Clean Hydrogen Industrial Hub	Western Australia	Up to A$70 million (US48.2 million)
Stanwell Corporation's Central Queensland Hydrogen Hub (CQ-H2 Hub)	Queensland	Up to A$69.2 million (US47.6 million)
Port of Newcastle's Port of Newcastle Hydrogen Hub	New South Wales	Up to A$41 million (US28.2 million)
Origin Energy's Hunter Valley H2 Hub	New South Wales	Up to A$41 million (US28.2 million)
South Australian Government's Port Bonython Hydrogen Hub	South Australia	Up to A$70 million (US48.2 million)
Tasmanian Government's Tasmanian Green Hydrogen Hub	Tasmania	Up to A$70 million (US48.2 million)

Source: HyResource (2022).

TABLE 11.3 List of announced hydrogen hubs under ARENA's Clean Hydrogen Industrial Hubs Program: Hub Development and Design Grants

Proposed hub	*State*	*ARENA funding*
ENGIE Pilbara Green Hydrogen Hub	Western Australia	Up to A$3 million (US$2.1 million)
Santos Carnarvon Clean Hydrogen FEED	Western Australia	Up to A$3 million (US$2.1 million)
Ark Energy Han-Ho H2 Hub Feasibility Study	Queensland	Up to A$2.42 million (US$1.67 million)
Origin Energy & ENEOS MCH Gladstone Project	Queensland	Up to A$1.25 million (US$0.86 million)
Vena Energy Euroa Energy Project	Queensland	Up to A$3 million (US$2.1 million)
Origin Energy Green Ammonia Project for Export (GRAPE)	Tasmania	Up to A$3 million (US$2.1 million)
INPEX Operations Darwin Clean Hydrogen Hub – Market Development Study	Northern Territory	Up to A$1 million (US$0.69 million)
Santos Moomba Clean Hydrogen FEED	South Australia	Up to A$3 million (US$2.1 million)
Zero Degrees Rosella 1 La Trobe Valley Blue Hydrogen	Victoria	Up to A$2.98 million (US$2.1 million)

Source: HyResource (2022).

generate multi-billion-dollar revenue for Australia as well as create new export opportunities and numerous new jobs.

The Low Emissions Technology Statement (Government of Australia 2021) indicates that the Australian government believes in technology-based solutions to climate change over financial mechanisms such as carbon taxes. By 2030, Australia wants to be among the top three largest hydrogen exporters to Asian markets and generate billions of dollars in export revenue. The presented estimates assume that in the best-case scenario, the hydrogen economy can create an additional A$26 billion (US$17.75 billion) in GDP and roughly 17,000 jobs by 2050 (COAG Energy Council Hydrogen Working Group 2019).

Utilization

The decarbonization of existing fossil fuel-based feedstocks (i.e., mainly ammonia and steel production) constitutes the obvious first step that Australia could take to use hydrogen. The country is among the top 20 ammonia-producing nations (1,582,000 tons produced in 2018, mainly for export; Coherent Market Insights 2020), and significant opportunities exist to upgrade ammonia plants to be able to use green hydrogen feedstock to reduce their carbon footprint. One advantage is that existing infrastructure does not require substantial investment to work with clean feedstocks. In addition, the decarbonization effort can be gradual, starting with just 5–10% of green hydrogen blended with gray hydrogen from steam methane reforming and steadily increasing the green hydrogen content thereafter. Some industry players in Australia are also considering using blue hydrogen, where CO_2 could be captured and stored in vast underground caverns. The first pilot project for the partial decarbonization of hydrogen feedstock for ammonia production to replace up to 30,000 tons of hydrogen from natural gas with green hydrogen from water electrolysis (the production of this plant is 850,000 tons per annum; Arenawire 2020) was announced by Yara International. Its existing ammonia plant in Dampier in Western Australia will trial solar-based green hydrogen production (Yara International ASA 2020). The project consists of a 10-MW electrolyzer, an on-site photovoltaic farm, and a battery storage system that will allow the plant to operate without being connected to the main electrical grid. Production is scheduled to commence in 2023.

Another obvious sector to deploy hydrogen to decarbonize existing feedstocks is Australia's steel industry. Steelmaking is responsible for approximately 8% of global CO_2 emissions (Hoffmann, Van Hoey, and Zeumer 2020). Despite Australia being the largest iron ore producer globally, its steelmaking operations are limited. The country produces only 5.5 million tons of crude steel per annum compared with approximately 920 million tons of iron ore (World Steel Association 2022). Green hydrogen production could thus lead to the establishment of local processing and steelmaking facilities in which iron ore could be converted into steel using green reductants such as hydrogen and its derivative, ammonia.

However, while the vision of green steel production in Australia is gaining momentum, some doubt remains about whether hydrogen is the ultimate route to achieve this goal. Some mining companies are exploring the use of biomass or biochar instead of fossil fuel-based reductants, while others are investigating alternatives such as molten oxide electrolysis and electrowinning processes (BHP 2022, Rio Tinto 2021). The cost of green hydrogen production coupled with high labor costs remain major limiting factors for the green steel industry in Australia, and no pilot green steel production projects using green hydrogen have thus far been announced.

Other minor local uses for hydrogen in Australia include hydrogen refueling stations and the production of green hydrogen for blending into existing natural gas pipelines (Reuters 2021), (Paul 2021). Several projects have been announced to use green hydrogen in remote towns and settlements that rely on diesel generators (Shafiullah et al. 2020). Mining companies have also shown interest in using hydrogen to decarbonize mobile mining applications. The remoteness of mining sites and excellent solar and wind conditions may allow some Australian mining operations to produce their fuel locally. One of the first mining companies to embrace this concept in Australia was Fortescue Metals Group. In 2020, Fortescue announced the deployment of 10 fuel cell coaches together with a hydrogen refueling station powered by a nearby solar farm in its Christmas Creek mine (Fortescue Metals Group Ltd 2020). It is also trialing the use of hydrogen-powered mining trucks, a move that could decarbonize a significant proportion of the fuel consumption of its mobile mining equipment (Parker 2021). Similarly, using hydrogen as a fuel in the aviation sector has gained significant momentum globally. While the clear early target for decarbonization in this sector lies in using biofuels, synthetic fuels produced from green hydrogen and captured CO_2 are the more likely solutions in the long run (Qantas 2021).

Most early- and pilot-phase hydrogen deployment projects in Australia have been supported and incentivized by federal and state government schemes (as described in the strategy and research sections). Since these early projects would not have been economically viable without financial support, the government has played an essential role in enabling first movers to introduce hydrogen projects. Such projects have aimed to prove the viability of hydrogen supply chains in Australia and develop the country's hydrogen expertise to reduce implementation risks. However, while many gigawatt-scale hydrogen projects have been announced in Australia, the largest electrolyzer systems remain those deployed in hydrogen refueling stations and various pilot and demonstration projects. The largest of these is the 1.25 MW Hydrogen Park South Australia operated by Australian Gas Networks (Australian Gas Infrastructure Group 2022).

While Saudi Arabia focuses on its flagship project of NEOM, multiple significantly larger projects have been announced in Australia including the 26 GW Asian Renewable Energy Hub backed by BP (BP 2022). Osaka Gas has entered into a joint venture with the proponents of the Desert Bloom Hydrogen project in the Northern Territory, which will see the generation of 10 GW of renewable energy for hydrogen production and export (Osaka Gas 2022). Meanwhile, Sun Cable is competing to supply energy to Singapore from its 20-GW solar farm (Northern Territory Government 2022). Finally, Kawasaki Heavy Industries delivered its first shipment of blue hydrogen to Japan from Latrobe Valley in Victoria (Hydrogen Energy Supply Chain 2022). These multiple multi-gigawatt-scale projects are viable contenders to Saudi Arabian hydrogen projects.

Australia and Saudi Arabia face some of the same challenges. For example, since both countries are looking at using seawater desalination to produce hydrogen, the required scale and volumes of produced brine will be a challenge. In particular, the brine discharge remains as-yet unaddressed. The Desert Bloom project in Australia is examining this issue by deploying water-harvesting devices that extract water from moist air (Potter 2022). While this solution is interesting, the high-power consumption of these devices will likely be a limiting factor. Another common challenge is the shortage of qualified workers. Australia noted such labor shortages early and deployed numerous programs at universities nationally to develop the country's hydrogen capability. Saudi Arabia is following a similar pathway by investing in university courses and programs to develop qualified hydrogen personnel. Among the opportunities for Saudi Arabia and Australia to collaborate are mining activities to supply the raw materials essential for enabling these large gigawatt-scale hydrogen projects.

One issue unique to Australia is cyclonic activity (Figure 11.1). Areas of the highest cyclonic activity often overlay with some of the best wind and solar resources in the country. As such, the project expenditure in those areas will rise significantly due to the increased cost of equipment certified for operations in cyclone-prone areas.

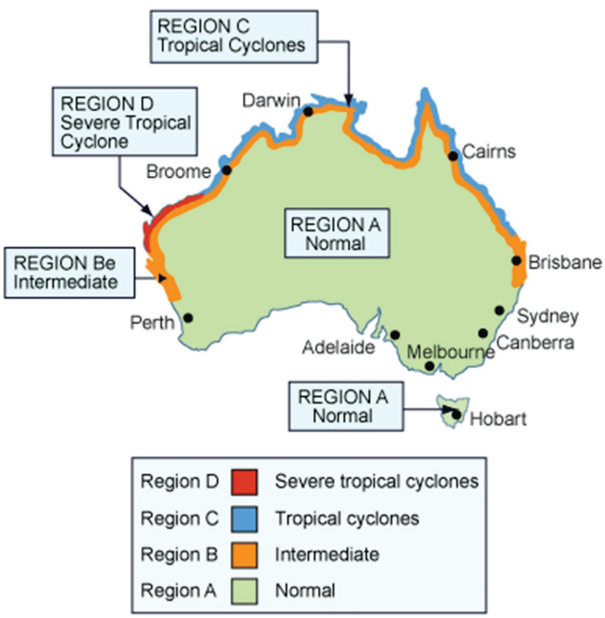

FIGURE 11.1 Map of cyclone-prone regions in Australia.

Source: RMIT (n.d).

Research

The national hydrogen strategy (COAG Energy Council Hydrogen Working Group 2019) distinguishes two implementation phases. Phase I revolves around building industry foundations and focuses on technology demonstrations. This initial phase, which is expected to last until 2025, aims to develop hydrogen supply chains and scale up technology by establishing demand centers (or 'hydrogen valleys'). Phase II focuses on large-scale market activation. It aims to define future actions and areas in which hydrogen can play a major role. Some of the areas outlined in the national hydrogen strategy report include the deployment of fuel cell vehicle fleets and establishment of refueling infrastructures. Hydrogen blending into existing natural gas networks is another alternative, as is industrial hydrogen usage to decarbonize ammonia and steel production. However, all these future endeavors will rely heavily on the outcomes of Phase I to better understand the economic consequences as well as the advantages, challenges, and market demand.

To facilitate Phase I, the Australian government has provided funding on a co-financing basis, where project proponents are often required to contribute at least 50% of the project costs. While the intellectual property typically stays with the project developer, the Australian government requires knowledge sharing to be incorporated in the project delivery (e.g., giving lectures and presentations, preparing publicly available reports). The government has also committed to providing R&D funding to commercialize emerging technologies that might bridge the gaps in the supply chain and reduce the final cost of hydrogen.

The majority of this funding is distributed through ARENA, which was launched in 2012 to facilitate the innovation and uptake of clean energy in Australia. Since its inception, ARENA has distributed A$1.75 billion (US$1.2 billion) in funding, supporting R&D, demonstration, and commercial projects nationally. Historically, ARENA's focus revolved around traditional renewable energy projects such as wind, solar, and battery storage applications. Although some smaller R&D-focused hydrogen projects were also funded, this focus changed in 2019 with the introduction of the national hydrogen strategy, when ARENA's focus pivoted to support hydrogen uptake.

The Clean Energy Finance Corporation (CEFC) is also playing a major role in enabling hydrogen R&D in Australia. The CEFC is a government agency that offers project investment through a wide range of financial products and structures. As such, it operates more like a commercial bank providing loans, including for demonstration and commercialization projects through the Clean Energy Innovation Fund (Clean Energy Finance Corporation 2022a). Part of the CEFC's remit is to support hydrogen projects through its A$300 million (US$205 million) Advancing Hydrogen Fund (Clean Energy Finance Corporation 2022b). In particular, this fund supports projects that address five areas of interest: hydrogen-based transportation, hydrogen feedstocks for industry, hydrogen-based power generation and balancing, fuel for industry, and fuel for buildings.

CSIRO is a leading research organization in the hydrogen space in Australia. The CSIRO Hydrogen Industry Mission was launched in 2021 to leverage CSIRO's hydrogen research capabilities with the government, industry, and broader research community partners. CSIRO has a long and successful history in the commercialization of hydrogen technologies. The now-defunct Ceramic Fuel Cells, one of the early leaders in solid oxide fuel cell technologies, was spun out from CSIRO (Fuel Cells Bulletin 2015). More recently, CSIRO has attempted to commercialize its ammonia cracking membrane technology through licensing agreements with Fortescue. It has also launched Endua, a startup backed by Main Sequence and Ampol. Endua aims to commercialize hydrogen-based energy storage technology suited for use in remote communities and mining operations that rely heavily on diesel generators (Kachel 2021).

Multiple universities in Australia have long conducted hydrogen-related research, including on novel membrane technologies, electrode and catalyst design, and electrochemical ammonia generation. Monash University has recently spun out novel electrochemical ammonia production technology under Jupiter Ionics (Monash University 2021). The technology will address the century-old and inefficient Haber–Bosch process by introducing a flexible and low-temperature ammonia production pathway. Moreover, the research by Monash University and the University of Wollongong on novel breathable membranes for hydrogen production has been commercialized by AquaHydrex in the United States (Monash University 2022a). Monash University has also attracted A$40 million (US$27 million) in funding from Woodside Energy as part of the Woodside Monash Energy Partnership to work on low-carbon energy solutions, including hydrogen (Monash University 2022b). Elsewhere, a group at the University of New South Wales has spun out LAVO technology, which can store energy in the form of hydrogen in the solid state (Fuel Cells Bulletin 2021). The technology comprises an electrolyzer, metal hydride hydrogen storage, and a fuel cell in a single device.

Australian government and research organizations have made significant efforts to engage and build relationships with the R&D sector in potential hydrogen offtake economies. Owing to common export–import interests, strong ties have particularly been established with research organizations in Singapore, Japan, and South Korea to co-develop or trial hydrogen supply chain technologies. As part of the broader hydrogen export strategy, the Australian government and research organizations are working toward establishing similar ties with other export destinations. Australia is also promoting hydrogen and fostering potential export opportunities as part of its membership of the Asia–Pacific Economic Cooperation (APEC Energy Working Group 2018).

In January 2020, the Ministry of Economy, Trade and Industry of Japan and the Department of Industry, Innovation and Science of Australia signed a Joint Statement on Cooperation on Hydrogen and Fuel Cells (Ministry of Economy, Trade and Industry of Japan 2020). In June 2021, the Australian and Japanese governments signed the Japan–Australia Partnership on Decarbonization through Technology (Ministry of Foreign Affairs, Japan 2021). The partnership acknowledges that both Japan and Australia believe in a technology-based response to climate change and reducing greenhouse gas emissions, while ensuring economic growth and job creation. This partnership builds on the countries' strong bilateral cooperation through initiatives and statements such as the hydrogen energy supply chain, Japan–Australia Energy and Resources Dialogue, and previously mentioned Australia–Japan Joint Statement on Cooperation on Hydrogen and Fuel Cells.

In March 2020, the Australian and Singaporean governments signed a memorandum of understanding to cooperate to find low-emission solutions (Department of Foreign Affairs and Trade, Government of Australia 2020). The priority areas of cooperation under this memorandum of understanding include long-term emission reduction strategies and low-emission pathways; hydrogen development; carbon capture, utilization, and storage; and renewable energy trading and measurement, verification, and reporting under the Paris Agreement.

Australia and Germany have collaborated on a feasibility study exploring the green hydrogen supply chain from Australia to Germany. The outcomes of this HySupply project will be shared publicly (GlobH2E 2021). HySupply is an excellent example of a novel public–private partnership involving governments, industry leaders, and research organizations.

The South Australian government and the Port of Rotterdam have released a prefeasibility study of hydrogen production in South Australia and export to Europe (Department of Energy and Mining, Government of South Australia 2021). The study concluded that the price of hydrogen in the form of ammonia delivered at the Port of Rotterdam will be €3.0–3.8 per kg (US$3.1–$4.0 per kg) assuming 2030 price levels. Moreover, 210,000 tons of hydrogen in the form of ammonia could be produced annually.

Case study

The hydrogen energy supply chain project in Australia aims—in its pilot phase—to demonstrate an integrated hydrogen supply chain encompassing production, storage, and transportation for delivering liquefied hydrogen to Japan (Figure 11.2).

The project also includes the design and operation of a specialized liquefied hydrogen carrier as well as the design of a marine vessel. Starting from brown coal gasification from coal resources in Latrobe Valley in Victoria, the produced hydrogen is liquefied and transported in specially designed shipping vessels from the Port of Hastings to Kobe in Japan. The produced CO_2 is then captured and stored in nearby underground caverns. With the arrival of the Kawasaki Heavy

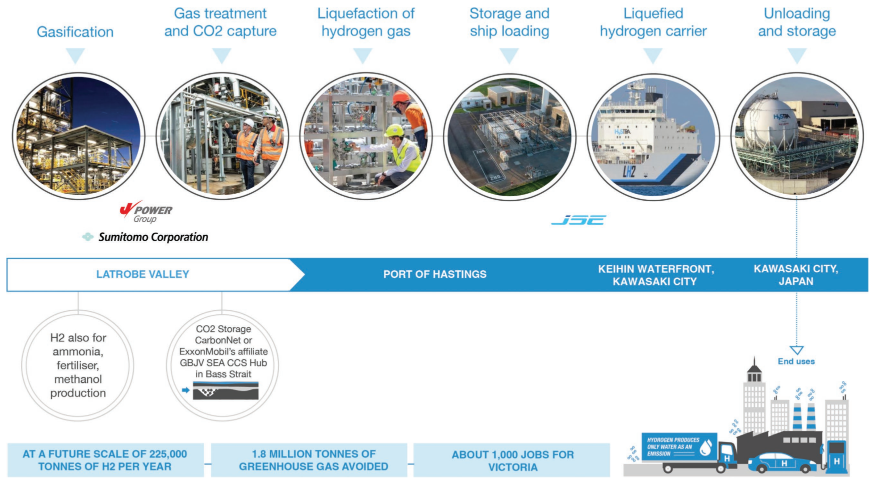

FIGURE 11.2 Hydrogen energy supply chain.

Source: Hydrogen Energy Supply Chain (2022).

Industries-built Suiso Frontier at the Port of Hastings, Victoria is predicted to become a significant focal point for Australia's hydrogen ambitions. The Suiso Frontier measures 116 m and has a gross tonnage of 8,000 tons or 1250 m^3 of liquid hydrogen (Hydrogen Energy Supply Chain 2022). By comparison, very large gas carriers that ship LNG and liquefied petroleum gas generally measure between 250 and 300 m and can load between 100,000 to 200,000 m^3 of gas.

The hydrogen energy supply chain project is being developed in two phases by several industrial players, including Kawasaki Heavy Industries, the Electric Power Development Co. (J-Power), Marubeni Corporation, Sumitomo Corporation, Iwatani Corporation, and AGL. The pilot phase, which began in January 2021, aims to demonstrate a fully integrated hydrogen supply chain between Australia and Japan, while the commercial phase will build on the outcomes of the pilot phase and produce up to 225,000 tons of liquid hydrogen annually by 2030 (Hydrogen Energy Supply Chain 2022).

The project's ability to be fully commercialized depends on the outcomes of the pilot phase as well as its technical feasibility, demand for hydrogen, regulatory approval, community feedback, and progress on carbon capture and storage technologies. The cost of this pilot phase is estimated to be A$500 million (US$342 million). A study published by Kawasaki Heavy Industries shows a total project cost of 744 billion yen (US$5.5 billion), with the majority of capital expenditure going toward hydrogen liquefaction (33%), followed by hydrogen production (30%) and

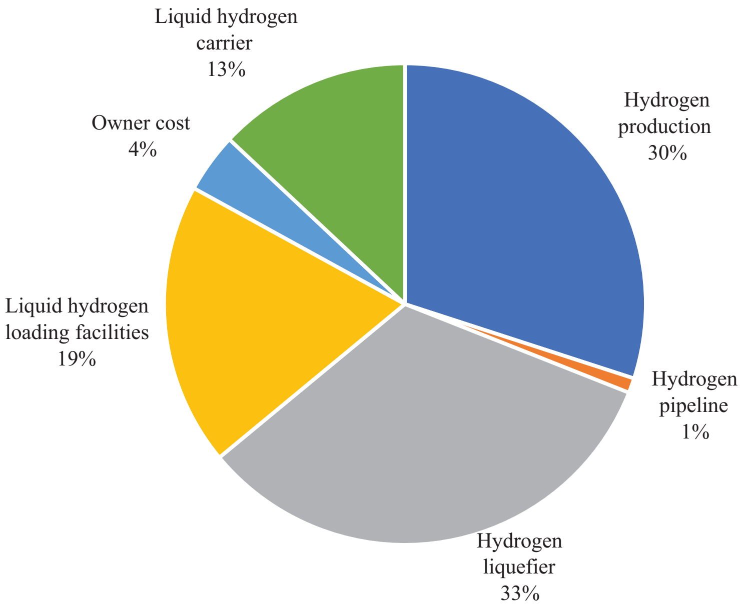

FIGURE 11.3 Cost breakdown for the hydrogen energy supply chain.

Source: Kamiya, Nishimura and Harada (2015).

a liquid hydrogen loading infrastructure (19%) (Figure 11.3) (Kamiya, Nishimura, and Harada 2015).

Kamiya, Nishimura, and Harada (2015) also present the cost breakdown of the hydrogen from Latrobe Valley delivered to Japan. The expected hydrogen cost at Kobe is 29 yen per Nm^3, corresponding to approximately US$0.21 per Nm^3, or US$2.34 per kg. This cost breakdown shows that the major contributors to the cost of hydrogen are hydrogen liquefaction (33%), followed by the cost of production (29%), loading infrastructure cost (11%), and carbon capture and storage cost (10%). The transportation costs from the Port of Hastings to the Port of Kobe account for only 9% of the total cost, while the brown coal feedstock for hydrogen production contributes a mere 8% (Figure 11.4).

Finally, the study compares the costs of the energy produced in Japan using different fuels as well as wind and solar generation (Figure 11.5). The electricity price based on hydrogen derived from brown coal from Latrobe Valley is significantly more expensive than nuclear electricity as well as LNG and coal-based power generation. However, hydrogen from Latrobe Valley is forecast to be a clean source of energy since the CO_2 emissions associated with its production have been captured and stored in Australia. According to the study, power generation from Latrobe

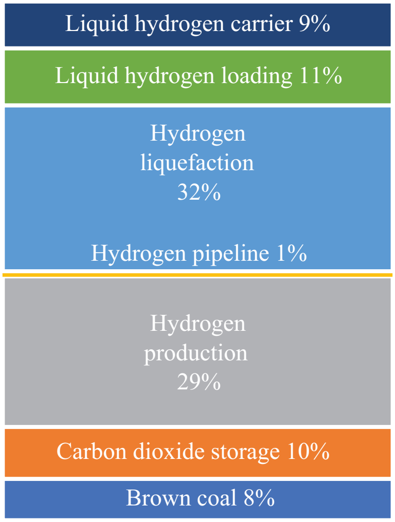

FIGURE 11.4 Breakdown of hydrogen costs from Latrobe Valley.

Source: Kamiya, Nishimura, and Harada (2015).

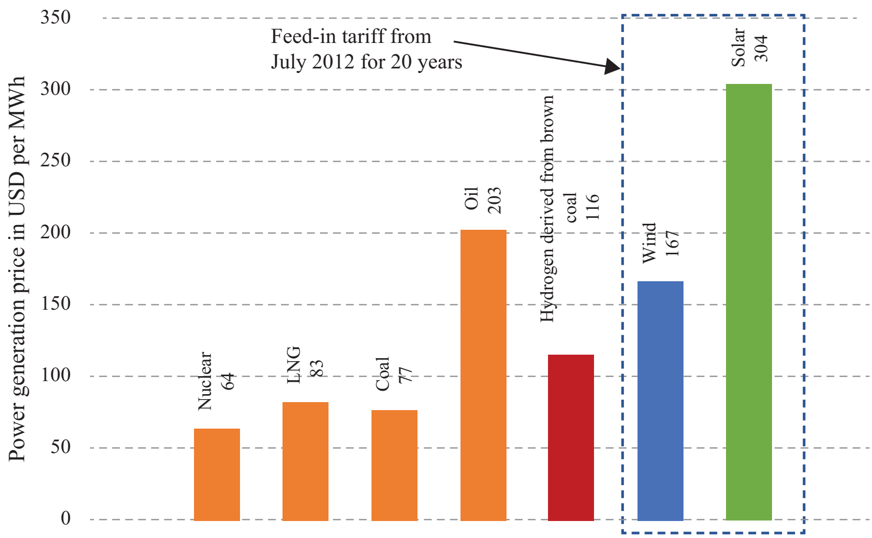

FIGURE 11.5 Comparison of the power generation costs in Japan based on different fuel sources (USD/MWh).

Source: Kamiya, Nishimura, and Harada (2015).

Valley's hydrogen is highly competitive with wind and solar generation in Japan. However, this comparison may need to be reviewed given that wind and solar generation costs have decreased significantly since the study was published in 2015.

When the study was first published, Kawasaki Heavy Industries predicted great potential for the hydrogen-based decarbonization of power generation in Japan, forecasting that up to 20% of primary energy in Japan would come from hydrogen by 2035 and that hydrogen's contribution to primary energy demand would increase to 40% by 2050 (Kamiya, Nishimura, and Harada 2015). In 2017, researchers from Kyushu University in Fukuoka reused the data from the Kawasaki Heavy Industry study to compare brown coal-derived hydrogen costs from Latrobe Valley with the prices of green hydrogen produced from solar energy in Karratha in Western Australia as well as solar and onshore wind energy-based hydrogen production and export to Japan from Gladstone in Queensland (Chapman, Fraser, and Itaoka 2017).

According to Chapman et al. (2017) the capital expenditure as well as operational and maintenance costs for solar hydrogen production in Karratha and solar and onshore wind production around the Gladstone area are twice the cost of the hydrogen produced from brown coal in Latrobe Valley. The higher cost is due to the costs of generating renewable energy and using electrolysis facilities. As before, the presented numbers may need to be revised since the costs of both wind and solar energy have decreased significantly over the last five years.

Finally, Chapman et al. (2017) compare the electricity production costs in Japan with those based on hydrogen sources. The worst-case scenarios for power generation in Japan based on green hydrogen from Karratha and Dampier are more than double the power generation costs compared with electricity from hydrogen produced from brown coal in Latrobe Valley. In the best-case scenarios, green hydrogen-based power is still at least 50% more expensive than the power produced from the hydrogen imported from Latrobe Valley.

The above studies indicate that producing green hydrogen in Australia and exporting it to Japan would be twice to four times more expensive (at today's renewable energy and electrolyzer prices) than fossil fuel-based power generation. The cost of blue hydrogen derived from brown coal is half as expensive as the cost of the green hydrogen produced in Karratha and Gladstone, yet still significantly more expensive than fossil fuels. Hence, achieving cost parity for green hydrogen and enabling future exports will continue to be challenging if a country such as Australia, which has some of the best wind and solar conditions globally, is still a long way off.

Conclusion

While Australia's export of raw materials and fossil fuels is a success story, the growing interest in hydrogen globally has proven to the Australian government that a new export industry might be emerging in the future. Australia is well positioned to meet this growing interest in hydrogen globally and create new highly specialized jobs and additional revenue. Its excellent wind and solar resources and abundance of land should position it among the world's leading hydrogen producers. However, the country's high labor costs and growing worker shortages could limit the viability of hydrogen projects. Water scarcity in Australia is also a growing issue, leaving hydrogen production to rely on seawater desalination. Further, its ports have insufficient capacity to support this new industry according to the scale of Australia's hydrogen vision. Hence, new infrastructure must be developed to enable and sustain the growth of hydrogen exports.

Australia's existing oil and gas industry could also benefit from this emerging industry by converting its resources into gray, blue, and turquoise hydrogen, which are significantly more cost-competitive than green hydrogen production. However, the colors of hydrogen create a certain division within the Australian population, and the ongoing public debate is expected to continue. While some Australians support economic growth, which can be delivered by general hydrogen production despite its color, others support green hydrogen only. By contrast, the Australian government seems to be color-agnostic when it comes to hydrogen production and its carbon intensity.

The options for using local hydrogen are limited. The most viable local uses for low-carbon hydrogen include for heavy-duty transportation, in ammonia production, and in refineries. Using such hydrogen in steelmaking is significantly further from commercial readiness due to the limited technology and high costs.

Australia's aim for its hydrogen economy is clear. By 2030, it wants to be among the three largest hydrogen exporters to Asian markets. The best-case scenario presented in the Australian hydrogen strategy assumes that the hydrogen economy can create an additional A$26 billion (US$17.75 billion) in GDP and close to 17,000 jobs by 2050 (COAG Energy Council Hydrogen Working Group 2019).

The hydrogen strategies of Australia and Saudi Arabia share some similarities, making them competitors in many respects. However, the significant distance between the countries indicates that they may serve different markets, except in Asia. For example, Saudi Arabia's proximity to European markets is expected to open up opportunities to export to Europe. Since both Australia and Saudi Arabia want to become pioneers in hydrogen exports, clear synergies from investing in technological development, scaling up, and running demonstration projects exist, which could benefit both nations equally.

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12

USING HYDROGEN FOR DECARBONIZATION, INDUSTRIAL DEVELOPMENT, AND ENERGY SECURITY

Shared ambitions for Japan, ASEAN Member States, and India

Yoshiaki Shibata, Victor Nian, Amit Bhandari and Jitendra Roychoudhury

Introduction

With the release of the Strategic Road Map for Hydrogen and Fuel Cells in 2014, Japan took the lead in shaping its national hydrogen strategy by leveraging decades of research and development (R&D) in the hydrogen field (METI 2014). Given its energy resource constraints, Japan has identified the need to collaborate to ensure the availability of clean hydrogen options for import, as the country is expected to be the key Asian market for imported hydrogen. As part of this initiative, it has focused on the twin challenges of technology push and market pull as it seeks to develop its domestic hydrogen economy and support the global development of hydrogen applications. Another crucial element of Japan's energy policy has been to diversify its energy sources to avoid supply disruptions and reduce vulnerabilities (Kitazume 2012).

A global focus on developing partnerships and collaborating is critical to the success of this diversification strategy. Following this strategy, Japan has developed the regional Asia Energy Transition Initiative (AETI) to help support the targeted countries move toward net-zero carbon emissions, while also developing hydrogen markets and supply options (METI 2021). The AETI also includes the Association of Southeast Asian Nations (ASEAN) and has recently been extended to cover India. This initiative and the Asia Zero Emission Community are indicative of a much closer alignment with ASEAN countries and India with regard to energy transition technologies and clean fuels such as hydrogen and ammonia (Japan Gov 2022). This makes it important to examine hydrogen development across the region (i.e., Japan, ASEAN member countries, and India).

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This chapter explores the evolution of hydrogen strategies in Japan, ASEAN member countries, and India. It also reviews the related research focus and delves deeper into the drivers shaping the role of hydrogen in ASEAN member countries and India. The case study section focuses on two cases involving the import of blue ammonia from Saudi Arabia and methylcyclohexane (MCH) from Brunei into Japan. The chapter concludes by drawing together the shared hydrogen strategies that focus on supporting the decarbonization of these economies and their common approach to ensuring energy security.

Japan

Japan is the world's third-largest economy with a gross domestic product (GDP) of $5 trillion and is among the largest importers of energy globally (JETRO 2022; IMF 2022). Over the past several decades, Japan's energy self-sufficiency has remained low. It is dependent on imports for almost 89% of its energy requirements, with its import dependence rising to 99.6% for coal, 97.8% for gas, and 99.7% for crude oil. Japan is also completely dependent on uranium imports for its nuclear power plants, with Australia, Canada, and Kazakhstan among its key nuclear fuel suppliers (World Nuclear Association 2021).

Fossil fuel consumption constitutes approximately 85% of Japan's primary energy mix. Further, the country's greenhouse gas emissions account for 3.5% of total emissions globally, ranking it among the top six countries worldwide (Statistics Bureau of Japan 2022). To curtail such emissions, it has been focusing on decarbonizing its economy as part of its commitment to the Paris Agreement of 2015 and subsequent climate change announcements. However, because of its geographical constraints, Japan has limited space to deploy the renewable energy resources needed to decarbonize its economy, requiring it to depend on imported clean or low-carbon hydrogen and other fuels such as ammonia.

Japan faced severe challenges in decarbonizing its power sector after its nuclear power plants were shut down in the wake of the Great East Japan Earthquake in 2011, and the rapid deployment of renewable energy at that time was not plausible. This explains why Japan has focused heavily on building large-scale hydrogen supply chains locally and internationally to ensure that imported clean hydrogen and domestically developed green hydrogen can be used to support the decarbonization ambitions of the country's power sector. Designing an international hydrogen supply chain that raises hydrogen imports is essential for Japan because the green hydrogen developed domestically is insufficient to decarbonize energy systems. Globally, interest in hydrogen as a potential source of decarbonized energy has increased exponentially, especially since the Paris Agreement.

A massive volume of inexpensive hydrogen is required to meet hydrogen demand in the power generation sector. Owing to limited natural resources in Japan, the only possible route for producing domestic hydrogen is green hydrogen. However, the cost of renewable energy in Japan remains above the international average. Thus, it must import hydrogen from regions and countries in which inexpensive hydrogen can be generated at large scale.

Japan has primarily focused on developing hydrogen technology to create a hydrogen market. However, this approach might need to be revised to shift its focus from technology push to market pull, as hydrogen costs should fall through technological development and market expansion. Japan must also diversify its hydrogen supply chain, both regionally and internationally, to meet its energy security needs. This has driven it to develop supply chains and invest in collaborations and partnerships.

Strategy

Japan's hydrogen development activities were triggered by the Great East Japan Earthquake in March 2011. However, there was a legacy of intensive R&D on hydrogen and fuel cells in the 1990s. The loss of nearly 50 GW of nuclear capacity after all reactors stopped operating following the earthquake has posed a challenge in decarbonizing power generation. The nuclear share of power generation decreased from 25% in 2010 (before the earthquake) to 0% in 2014. Over the same period, the shares of liquefied natural gas (LNG) and coal increased by 14% and 6%, respectively, whereas that of renewables increased by only 2% (METI 2020). Faced with the pressures of decarbonization, Japan has thus focused on building a large-scale hydrogen supply chain overseas to import hydrogen to meet its power generation requirements.

Against this background, the Strategic Road Map for Hydrogen and Fuel Cells was formulated by the Ministry of Economy, Trade and Industry (METI) in 2014. It laid out targets for the deployment of fuel cell electric vehicles (FCEVs), hydrogen refueling stations (HRSs), and stationary fuel cells. The target landed price (to be reached in the mid-2020s) of imported hydrogen was set at Japanese Yen (JPY) 30/Nm^3 ($3/kg) (METI 2014). The Strategic Road Map was revised in 2016 and 2019 to set numerical targets for fuel cells and electrolyzers (METI 2019). Figure 12.1 illustrates the targets and the progress toward these targets.

Meanwhile, the Ministry of the Environment and other ministries have started hydrogen initiatives such as demonstrating and piloting domestic hydrogen production from renewable energy and fuel cell development. At the Ministerial Council on Renewable Energy, Hydrogen, and Related Issues in April 2017, Prime Minister Abe requested that the relevant ministers formulate a strategy for hydrogen-related policies that should unite all ministries. In response to this request, the Basic Hydrogen Strategy was developed in December 2017 (METI 2017) by the Ministry of Land, Infrastructure, Transport, and Tourism, the Ministry of Education, Culture, Sports, Science, and Technology, and the Cabinet Office. The Basic Hydrogen Strategy presents an action plan for meeting Japan's objectives by 2030 and 2050. The strategy sets the goal that Japan should reduce hydrogen costs to the same level as those of conventional energy and provide integrated policies across ministries

	FC Trucks	FC Buses	FC Forklifts	FC Cars	Refueling Stations	Electrolyzers	Stationary FC
Current Status	-	120	397	7,457	183	-	420,000
Targets							
By 2020	-	100	500	40,000	160	-	-
By 2025	-	-	-	200,000	320	-	-
By 2030	-	1,200	10,000	800,000	1,000	Energy Consumption (kWh/Nm3) 4.3 (Alkaline) 4.5 (PEM)	3.0 million

FIGURE 12.1 Hydrogen targets in Japan.

Source: Authors, based on IPHE Country Update, November 2022 (IPHE 2022).

ranging from hydrogen production to utilization to achieve this goal. The aim is to reduce the import price of hydrogen from JPY 30/Nm^3 to JPY 20/Nm^3 by 2030 by expanding international hydrogen supply chains, thus highlighting the critical role played by international collaboration. The target import prices align with the 2014 Strategic Road Map for Hydrogen and Fuel Cells.

To achieve the goals outlined in the Basic Hydrogen Strategy, the Strategic Road Map for Hydrogen and Fuel Cells renewed in 2019 (METI 2019) defines new targets for the specification of essential technologies. It also includes a breakdown of the costs of related technologies such as hydrogen production from fossil fuels, carbon capture and storage, electrolysis, hydrogen carriers, hydrogen-fired power generation, fuel cells for mobility, and combined heat and power. Further, it presents the measures necessary to achieve these goals and demands that Japan convenes a working group of experts to review the implementation status of each area stipulated by the Road Map.

Momentum accelerated after October 2020 when Prime Minister Suga took over from Prime Minister Abe and announced the goal to achieve carbon neutrality by 2050. The Green Growth Strategy formulated in response to this announcement in June 2021 set a quantitative target for hydrogen demand, including ammonia, for the first time in Japan (METI 2020). This target was 3 million tons of hydrogen (3 million tons of ammonia is equivalent to 0.5 million tons of hydrogen) by 2030 and approximately 20 million tons of hydrogen by 2050. The breakdown of hydrogen demand, including ammonia, by sector is estimated to be 5–10 million tons of hydrogen/ammonia for the power generation sector, 6 million tons for mobility, and 7 million tons for industry.

The Sixth Strategic Energy Plan formulated in October 2021 revealed for the first time the targeted share of hydrogen and ammonia in the power generation mix by 2030 (METI 2021). This plan aims to produce approximately 15 TWh of hydrogen and ammonia power, which will account for approximately 1% of total power generation by 2030. In June 2023, Japan revised its target to increase hydrogen supply to 12 million tons by 2040, investing $107.5 billion over the next 15 years, and further to 20 million tons by 2050 (Reuters 2023).

Hydrogen is a key alternative for decarbonizing energy systems. Additionally, the Japanese government perceives it as an opportunity to develop hydrogen-related industries. The government and private sector have collaborated closely in the research, development, demonstration, and deployment of hydrogen and fuel cells over the past couple of decades. Consequently, many private companies are playing an essential role in building hydrogen supply chains, including production, storage, transport, and application. As hydrogen gains momentum as a crucial factor for meeting carbon neutrality ambitions globally, exporting hydrogen and fuel cell technology as well as developing the related infrastructure would be a tremendous opportunity for Japan.

However, the cost of hydrogen remains a critical challenge. To reduce this cost, continued technological development in all sectors, including production, transport, storage, and application, is required. Simultaneously, financial support mechanisms and regulations for potential hydrogen users are also needed. The Carbon Contracts for Difference concept proposed by the European Commission is a possible instrument (European Commission 2020). Its basic idea is to remunerate investors by paying the difference between the CO_2 reduction cost and CO_2 price in the Emissions Trading Scheme as a reference cost. However, as no emissions trading scheme has thus far been introduced in Japan, the reference CO_2 reduction cost would need to be debated and set.

Regarding the regulations that force potential hydrogen users such as utilities and the industrial sector to use a certain amount of hydrogen, care is required. Historically, Japan's industrial sector has strongly opposed regulations on energy use and CO_2 emissions. Instead of regulations, the industrial sector has presented a voluntary action plan for decarbonization (Toyoda 1997). However, further discussions on cost-effective measures, regulations, and non-binding voluntary actions are required in Japan.

Engagement with Saudi Arabia is a key part of its approach to hydrogen supply chain development. Leveraging their long history of trade and diplomatic relations, going back to 1955, the two countries established the Joint Group for Saudi–Japan Vision 2030 in September 2016 to help channel opportunities for cooperation. Of the nine themes[1] identified, the energy theme focused on collaborating to study low-carbon energy system technologies, including carbon capture and storage and hydrogen (MOFA 2017). Following the signing of the memorandum of cooperation in the energy sector in September 2016, Japan and Saudi Arabia agreed to collaborate on the development of carbon capture, utilization, and storage (CCUS) and hydrogen. Under this framework, the Institute of Energy Economics in Japan and Saudi Aramco co-hosted a workshop on CCUS and hydrogen in September

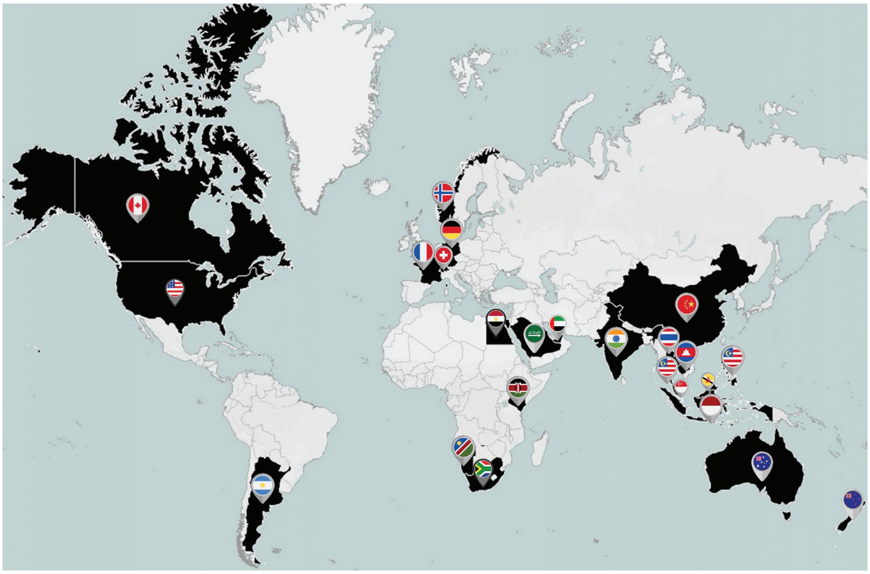

FIGURE 12.2 Japanese bilateral partnerships focused on hydrogen.

Source: Authors' visualization based on published data (CSIRO 2022).

2017. The framework engagement and heightened cooperation between the two countries resulted in the world's first blue ammonia shipment, as detailed in the case study section in this chapter (METI 2018).

To build stable international hydrogen supply chains for procuring affordable hydrogen, Japan has engaged in bilateral partnerships with countries such as Argentina, Australia, and Saudi Arabia (Figure 12.2). These relationships have been established through government agreements and memoranda of understanding (MoUs) on cooperation on hydrogen-related technology development and the implementation of pilot projects. These countries have huge potential for producing clean hydrogen, either renewable or fossil fuel and carbon capture and storage-based and are expected to be Japan's hydrogen suppliers.

Utilization

Approximately 2 million tons of hydrogen is used in Japan, most of which is produced and used in heavy industries such as refineries, petrochemicals, and chemicals (METI 2021). A limited volume of hydrogen (approximately 30,000 tons) is consumed in light industries such as semiconductors, metals, and glass. Industrial gas suppliers play a role in hydrogen delivery by installing on-site electrolyzers on customers' premises and transporting hydrogen from heavy industries in compressed gas in tube trailers or liquid form in tanker trucks. Hydrogen pipelines exist but only in limited industrial zones.

Since the end of 2014 when they were launched in the market, 7,457 FCEVs have been operating in Japan. By the end of 2022, 169 HRSs were under construction, consuming almost 657 tons of hydrogen annually[2] (METI 2022). Most FCEVs are used in passenger fleets. Fuel cell applications for heavy-duty vehicles such as buses, trucks, and ships are also being developed.

In Japan, power generation is the most promising sector for future hydrogen applications, including ammonia. Decarbonizing power generation by using hydrogen is vital because of political and social acceptance issues in nuclear and rapid large-scale renewable energy deployment. The renewable energy share in power generation in 2020 was 20%, and the Sixth Strategic Energy Plan aims to increase this to 36%–38% by 2030 (METI 2021). Theoretically, the potential of renewable energy is sufficiently high to meet electricity demand. However, large-scale grid integration measures such as strengthening interregional transmission lines and introducing energy storage are required to explore the potential. Introducing such measures could increase the cost of the entire power grid even if renewable energy decreases. Technological development to overcome the technical challenges in using hydrogen is ongoing for a variety of options for power generation. This includes co-firing hydrogen with gas turbines, using 100% hydrogen in gas turbines, co-firing ammonia with coal-fired steam turbines, and using 100% ammonia in steam turbines.

Transporting large amounts of hydrogen over long distances is extremely difficult because it is gaseous at standard temperature and pressure. Hydrogen must be liquefied or converted into other chemical forms to transport large amounts of hydrogen cost-effectively. Regarding the options to import hydrogen, liquefied hydrogen (LH), liquid organic hydrogen carrier (LOHC), ammonia, and carbon-neutral methane systems are potential options. Recent technological developments for LH and LOHC systems began in 2012 under the framework of the R&D and demonstration projects of the New Energy and Industrial Technology Development Organization (NEDO), supported by the Japanese government (HYSTRA 2022; AHEAD 2017). The world's first LH vessel (Suiso Frontier) was launched in December 2019. After it was tested, the vessel departed Kobe Port in Japan for Hastings Port in Australia in December 2021 and returned to Kobe Port loaded with LH in February 2022. Hydrogen shipping using an LOHC system (toluene-MCH) from Brunei to Japan (detailed in the case study section) has been piloted, and hydrogen was supplied to a gas turbine in May 2020 (Crolius 2017). Although LH and LOHC systems require R&D and demonstration, ammonia is an existing hydrogen carrier with a mature and commercialized technology. Ammonia can be used as a fuel for power generation, especially for co-firing with coal, as its combustion performance is similar to that of pulverized coal. Owing to these benefits, the world's first pilot study on ammonia shipping from Saudi Arabia to Japan was conducted in September 2020 (as detailed in the case study section). Many private Japanese companies, including those in the power generation sector, plan to import ammonia.

Carbon-neutral methane has drawn considerable attention as an option to apply the existing technology and infrastructure. Clean hydrogen can be coupled with CO_2 and converted to synthetic methane under the existing LNG infrastructure. CO_2 can be captured from fossil fuels, biomass, or the atmosphere and then combined with hydrogen and remitted through the combustion process. This means that CO_2 is recycled, regardless of the CO_2 resource. However, clean hydrogen can significantly lower the carbon intensity of synthetic and carbon-neutral methane. In particular, gas utilities focus on carbon-neutral methane to decarbonize city gas without changing the existing infrastructure considerably. A Japanese gas company and Malaysian petroleum company have agreed to collaborate on a feasibility study to build a synthetic methane supply chain.

In addition to the power generation sector, the industrial sector has recently attracted attention, as indicated by its carbon neutrality. Hydrogen feedstocks for chemicals, refineries, and the direct reduction of iron and steel are candidates. However, challenges regarding technological readiness and cost-effectiveness remain.

There has been considerable effort to overcome the chicken-and-egg problem in Japan's mobility sector. Japan H_2 Mobility was established by 25 private companies, including automobile manufacturers, gas utilities, oil suppliers, and financial institutions (Toyota-Tsusho 2018). The objectives of the consortium are to strategically construct and operate HRSs through collaborations among stakeholders, such as arranging negotiations between the local government and HRS developers to smooth the licensing or assessment process and leverage finances. Automobile manufacturers also provide financial support for the construction of HRSs. Japan H_2 Mobility aims to construct 80 HRSs by 2027.

Linking supply and demand is crucial to the international hydrogen supply chain. Japan's LNG experience provides a hint for overcoming the chicken-and-egg problem. When LNG was first imported to Japan in 1969, electric power utilities, gas utilities, financial institutions, and the government collaborated to make it happen. Five success factors in the commercialization of LNG are notable. The first is the existence of air pollution regulations (SOX and NOX) that have facilitated a shift from oil and coal to gas. Second, tax incentives (duty-free) have made gas competitive with oil. Third, subsidies for equipment that enable the calorific adjustment of gas have alleviated the burden on consumers. Fourth, the commercialization of LNG has been backed financially by a government guarantee. Finally, the aggregation of bulk demand (electricity and gas) has brought about scale advantages. A similar collaborative framework is required to realize hydrogen imports.

Research

Various studies on hydrogen have been conducted in Japan, most under the initiative of NEDO, led by the METI. NEDO, founded in 1980, has been involved in developing a wide range of technologies. Concerning hydrogen, its primary research focuses on hydrogen carriers such as LH and LOHC systems, including storage, as these technologies are critical to building an international hydrogen supply. Other basic research includes fuel cells and electrolysis that aim to reduce the hydrogen production cost. One unique technology is toluene direct electrolysis (with water) to produce MCH, which is expected to reduce the hydrogen supply chain cost, as this mechanism can avoid producing and storing hydrogen. In addition, research on the components of HRSs such as hydrogen tanks, dispensers, and tubes is also being conducted to overcome regulations on industrial high-pressurized gas and reduce the cost of HRSs.

Demonstration projects have been conducted both locally and internationally. NEDO has led various feasibility studies on local hydrogen production and utilization within and outside Japan and proceeded to the demonstration phase based on the results. These projects aim to build a hydrogen supply chain as early as possible, even at a smaller and distributed scale.

In programs for the technological development of residential stationary fuel cells and large-scale field tests for fuel cells led by NEDO, fuel cell developers have collaboratively shared technologies, particularly auxiliary machines. Such collaboration has played a crucial role in reducing fuel cell costs and resulted in commercialization. This experience shows that the sharing of technical know-how among private companies can be essential for bringing new technologies to the market. However, after commercialization, competition becomes an important factor in bringing about economies of scale and lowering costs.

The momentum of hydrogen is increasing worldwide owing to decarbonization aspirations, which means that the market needs hydrogen in addition to other clean energies. However, because hydrogen is expensive, financial incentives and regulations are essential to create demand. Such incentives and regulations will cause the market to expand, leading to a decrease in hydrogen costs. A national energy strategy would show a concrete and clear future picture of hydrogen demand and the market to draw efforts from the private sector and investment from financial institutions.

ASEAN countries

Home to approximately 700 million people and with a combined GDP of more than $3.2 trillion, ASEAN economies (Figure 12.3) are an important part of the regional and global economy (Council on Foreign Relations 2022).[3] The ASEAN region is a critical export hub and a key part of global supply chains across multiple sectors from electronics to services (Lee and Adam 2022). The 2021 ASEAN Development Outlook states that the ASEAN region could cumulatively become the fourth-largest global economy by 2030 (ASEAN Development Outlook 2021). Its economic growth is energy-intensive, however. Singapore and Brunei are among the top 10 countries with the highest per capita energy consumption. Further, the

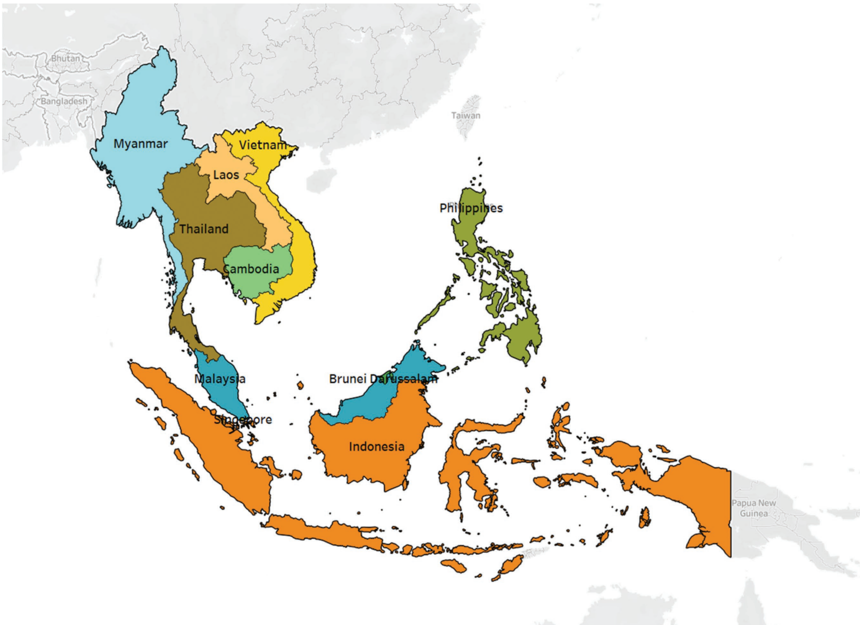

FIGURE 12.3 Map of ASEAN countries.

Source: Authors.

growth in energy consumption in the region has soared over the past two decades. For example, total final energy consumption in 2021 was almost 1.5 times the 2005 level. Such growth is expected to continue given the future economic growth prospects of the region coupled with its favorable demographics (61% of the population is below 35) (Lee and Adam 2022; ASEAN Energy Outlook 2022).

The primary energy demand of ASEAN member states is projected to triple from the 2020 level of 385 Mtoe, reaching 1,280 Mtoe by 2050 (ASEAN Energy Outlook 2022). Electricity demand in the region is expected to nearly triple by 2050, increasing from 1,126 TWh in 2020 to 3,388 TWh by 2050. By that year, fossil fuels, especially coal, will remain the largest source of electricity generation, with a share of 33.8% of installed capacity, with natural gas contributing 26.1%. The increasing consumption of fossil fuels will increase CO_2 emissions from 1,815 million tons in 2020 to 6,704 million tons by 2050 in the baseline scenario[4] (ASEAN Energy Outlook 2022).

The hydrogen ambitions of the ASEAN region focus on decarbonizing the economy, ensuring energy security, and diversifying energy resources (ASEAN Energy Outlook 2022). ASEAN member states have focused on collaboration to address regional and global energy security challenges. These collaborative efforts highlight their capacity to explore R&D opportunities and the strategic nature of the regional partnerships that have developed. The ASEAN region is close to the developing hydrogen markets of Japan and South Korea. This locational advantage could have competitive ramifications for hydrogen exporters such as Saudi Arabia and Australia in these key markets. The investments in the ASEAN region by Japan and Saudi Arabia highlight its logistical advantages and ongoing engagement with key regional stakeholders. These investments by Japan and Saudi Arabia have led to the exploration of hydrogen supply chain pilots and hydrogen production, respectively. The following section highlights current and prospective hydrogen-related policy developments within ASEAN member states.

Hydrogen policy in ASEAN member states

ASEAN economies rely on fossil fuels, and this carbon emission-intensive domination of their energy mix is expected to continue in the short term. Hydrogen is an attractive energy storage medium that can balance the intermittency of electricity generated from renewables, support countries' decarbonization ambitions, diversify fuel sources, and fulfill energy security goals and emission ambitions (ASEAN Centre for Energy 2022). In Phase II of the ASEAN Plan of Action for Energy Cooperation (2021–2025),[5] ASEAN member states have targeted a renewable energy share in the total primary energy supply of 23% and a 35% share in overall installed capacity (ASEAN Energy Outlook 2022). The ASEAN region could generate rich renewable energy resources, with theoretical estimations projecting gross capacities of 8,000 GW of solar energy, 229 GW of wind energy, 158 GW of hydro energy, 61 GW of biomass, and 200 GW of geothermal energy (Suryadi et al. 2021).

According to the baseline scenario in the 2022 ASEAN Energy Outlook project, the renewable energy share in the total primary energy supply will decline to 11.9% by 2050 compared with 14.2% in 2020 (ASEAN Centre for Energy 2022). To help increase the share of renewables in the total primary energy supply needed to meet emissions ambitions, it is thus critical to explore the potential of hydrogen as an energy storage option, especially in the transport sector (Suryadi et al. 2021). Seven of the 10 ASEAN member states have already announced carbon neutrality targets by 2050 (Handayani et al. 2022). Of the remaining three, Indonesia has committed to achieving its net-zero ambitions by 2060, while Thailand has stated that it will meet its net-zero target by 2065; the Philippines has yet to announce a specific target (Royal Thai Embassy 2022; Zheng 2022). Hydrogen is thus a key strategy for the ASEAN region to achieve its ambitious renewable energy targets, acting as an energy storage solution, ensuring the increased utilization of renewable energy resources, and helping develop new industries, leading to economic growth and additional jobs (ASEAN Climate Change and Energy Project (ACCEPT) 2020).

ASEAN member states are dependent on crude imports for approximately 40% of their total oil demand and this demand is primarily driven by the transport sector.

The electrification of the transport industry, along with the use of hydrogen directly and in fuel cells, would help ASEAN member states meet their emission goals and address their energy security requirements (Suryadi et al. 2021). However, the ASEAN region has huge disparities in economic prosperity, energy consumption, and access to energy sources. Its industrial capacity, access to technical and financial resources, and dependence on fossil fuels also vary regionally. These disparities provide opportunities for ASEAN member states to collaborate among themselves as well as reach out to external stakeholders. Countries outside the ASEAN region can provide access to technical know-how, along with long-term financing, to help jump start the region's hydrogen economy. For instance, Japan is well placed to provide long-term financial support and access to proprietary hydrogen technologies. In return, it gains access to a supply of hydrogen that can help diversify its global sourcing options. The sections below focus on the hydrogen strategies of the ASEAN member states.

Brunei Darussalam

Brunei is one of the richest ASEAN countries, second only to Singapore in terms of per capita income (Xinhua 2020a). Its per capita electricity consumption is also high, again second only to Singapore regionally (Bhutada 2022; Choo, Merdekawati and Putra 2022). Brunei's economy is almost entirely dependent on the exports of fossil fuels (almost 55% of Brunei's GDP of $35.5 billion is generated from oil revenues), including natural gas and oil, to power its economic development (IEA 2021; IMF 2022; Shani 2019). Brunei, along with Malaysia and Indonesia, is one of the few ASEAN countries that have an LNG export infrastructure. Its key export markets for LNG are Japan and South Korea, followed by China, India, and Taiwan (Kimura et al. 2020; Suryadi et al. 2021).

Brunei has targeted net-zero emissions by 2050, and it plans to increase its share of renewables in the power generation mix to 30%. In the current mix, fossil fuels constitute 98%, with diesel and solar photovoltaic-based generation accounting for the remaining 2%. Brunei's installed (primarily gas-fired) electricity generation capacity is 889 MW. Its solar photovoltaic generation capacity is 1.2 MW at a pilot project at Tenaga Suria Brunei and 3.3 MW at a relatively new solar installation at the Brunei Shell Petroleum flagship solar photovoltaic plant, Seria (Chikkodi 2021; Shani 2019).

As a small coastal country with a high forest cover of almost 72%, Brunei faces the challenge of land availability for installing a renewables infrastructure (United Nations General Assembly Debate Statement 2022). However, its relative advantage as a gas-rich country could allow it to produce blue hydrogen through a steam methane reforming process with CCUS. This might be a much more plausible pathway to increase hydrogen availability, from both the domestic use and the export perspectives. In 2017, the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) initiated a hydrogen supply chain demonstration project to deliver hydrogen to the country (Chiyoda Corporation 2017).

The AHEAD consists of four Japanese companies (Chiyoda Corporation, Mitsubishi Corporation, Mitsui & Co. Ltd. 2021b, and Nippon Yusen Kabushiki Kaisha) (NEDO 2017). The hydrogen supply chain demonstration system has an annual production capacity of 210 tons of hydrogen, which can supply 40,000 hydrogen fuel cell vehicles once transported to Japan. The demonstration project is discussed in detail in the case study section.

Brunei has steadily transitioned toward much more sustainable economic development in line with its strategic goals of improving its oil and gas sector, increasing the renewable energy share in its energy mix, and maximizing the economic development opportunities that arise through the transition (Shani 2019). In line with these goals, it has restructured its Energy and Industry Department, which functioned under the Prime Minister's Office, into the Ministry of Energy, Manpower, and Industry (Shani 2019). However, certain factors are limiting its focus to the hydrogen sector (Choo, Merdekawati, and Putra 2022; Energy Department, Prime Minister's Office 2014). These constraints include its geographical size, ability to develop new technologies to reduce the carbon footprint of its oil and gas industry, and target of reducing the country's energy intensity by 45% by 2035. The case of Brunei illustrates the benefits of collaborating with Japan and provides a framework for a potential business model for the export of blue hydrogen from the region.

Indonesia

Indonesia is the largest economy in the ASEAN region, with a GDP of $1.18 trillion; moreover, it has the fourth-largest population globally, with more than 270 million people spread over 17,499 islands (World Bank 2022). In 2021, Indonesia's final energy consumption was 127.4 Mtoe (Handbook Of Energy & Economic Statistics Of Indonesia (HEESI) 2022). It is the world's third-largest coal producer after China and India and the world's largest coal exporter (World Bank 2022). Fossil fuels account for approximately 87% of its primary energy supply (IEA 2021; Handbook Of Energy & Economic Statistics Of Indonesia [HEESI] 2022). Indonesia, previously an oil exporter, now depends on crude oil imports to meet its energy requirements, thus driving the need for energy security. Its transportation industry is one of the largest energy-consuming sectors (accounting for 42% of total energy consumption). Hence, Indonesia is promoting biofuels and electric vehicles to reduce its dependence on oil imports and meet the growing demand for liquid fuel from the ever-increasing transport sector (Reuters 2021). Indonesia has targeted net-zero emissions by 2060. Under its Long-Term Strategy for Low-Carbon and Climate Resilience 2050 (LTS-LCCR 2050), it plans to reduce greenhouse gas emissions by 32% by 2030 using its own resources. This percentage could rise to 43.2% subject to receiving international support (Violleta and Liman 2022).

As early as 2014, hydrogen was included in its National Energy Policy; however, Indonesia has not yet drafted a standalone hydrogen policy (Adiatma and Kurniawan 2022; Government of Indonesia 2014). Instead, it has incorporated plans to produce green hydrogen and use CCUS technologies to meet its emissions reduction targets as part of the LTS-LCCR 2050. Renewables constitute only 12.16% of the total primary energy supply, of which solar, wind, and geothermal energies constitute 0.05%, 0.07%, and 1.99%, respectively (Handbook Of Energy & Economic Statistics Of Indonesia (HEESI) 2022). As part of its long-term plan to reduce carbon emissions, Indonesia plans to increase its share of renewables in the energy mix to 23% by 2025 and 31% by 2050 (ASEAN Centre for Energy (2022)).

In particular, it plans to use the currently underexploited renewable energy potential of 3,686 GW (cumulatively across the solar, wind, hydro, and geothermal fields) to produce green hydrogen (Yep and Nugraha 2022). The development of green hydrogen in the Indonesian electricity sector will start in 2031 and continue until 2060 (Ministry of Energy and Mineral Resources, Republic of Indonesia 2022). A hydrogen generation capacity of 328 MW from 2031 to 2035 is expected, with an additional capacity of 332 MW from 2036 to 2040 and larger capacity expansions of 9 GW from 2041 to 2050 and 52 GW from 2051 to 2060 (Adiatma and Kurniawan 2022). However, a net-zero roadmap developed by the National Energy Council offers a different set of targets, indicating that consensus on strategy and targets is lacking (Adiatma and Kurniawan 2022).

The National Research and Innovation Agency[6] has been investing in R&D into proton-exchange membrane (PEM) electrolysis and fuel cell technology since 2011. In 2018, Toshiba Energy Systems & Solutions Corporation (Toshiba) and Badan Pengkajian dan Penerapan Teknologi signed an MoU on the implementation of an off-grid energy supply system called H2One (Toshiba 2018). H2One would generate power through hydrogen fuel cells, which would use the hydrogen produced by electrolyzers using electricity from renewable energy sources. This would enable the system to provide clean and stable energy without being affected by intermittency (an ideal off-grid solution for the archipelago of Indonesia) and displace diesel gensets from remote islands. Operating under Indonesia's Electricity Power Supply Business Plan, the state-owned electricity companies Perusahaan Listrik Negara and Toshiba signed an MoU to accelerate the adoption of such a system (Toshiba 2019). As part of the AETI, Japan has been working closely with Indonesia to support the energy transition program. Under the AETI, the governments of Japan and Indonesia signed a memorandum of cooperation in January 2022. This memorandum aimed to encourage cooperation to achieve their respective national emissions targets as well as develop and implement energy transition technologies such as hydrogen, ammonia, and CCUS, along with knowledge sharing and capacity building (Antara News 2022). In 2013, Japan established the Joint Crediting Mechanism in Indonesia to incentivize Japanese companies to invest in low-carbon development projects that contribute to sustainable development (JCM 2013). Several Japanese companies have expressed interest in pursuing pilot projects in Indonesia, focusing on blue and green hydrogen. These include Inpex, Mitsubishi, and TEPCO (Evans 2022, Hydrogen Central 2022a, Tepco 2022). The

Indonesian government has estimated that an investment of up to $25 billion is required to help start developments in this regard. Indonesian companies such as the state-owned Pertamina are also planning to invest up to $12 billion by 2026 to meet their renewable energy target of adding 10 GW of clean power generation capacity (Nathan 2021).

Along with Japan, South Korea is also active in Indonesia. In early 2022, Samsung and Hyundai announced plans, in collaboration with the Global Green Growth Institute, to develop a large-scale green hydrogen-based ammonia production project. The project, based in North Sumatra, uses geothermal energy to produce green hydrogen. The Global Green Growth Institute, along with the Korea Gas Corporation, will explore shipping green ammonia for use in South Korea (GGGI 2021; Global Energy Infrastructure 2022). The South Korean SK Group's SK E&S is also exploring opportunities related to hydrogen in Indonesia and has signed an MoU with PT Perusahaan Gas Negara, the state-owned Indonesian gas company (LNG Prime 2022).

Malaysia

Malaysia is the fifth-largest economy in the ASEAN region, with a GDP of $372.75 billion (IMF 2022). Fossil fuels account for approximately 92% of Malaysia's primary energy supply (IEA 2021; Suruhanjaya Tenaga 2021). It has targeted achieving carbon neutrality by 2050 (ASEAN Centre for Energy (2022)). As part of its Nationally Determined Contribution under the United Nations Framework Convention on Climate Change, Malaysia has targeted reducing its economy-wide carbon intensity by 45% by 2030 compared with 2005 levels (ASEAN Centre for Energy (2022)). It plans to increase the share of renewables in its electricity generation mix to 31% by 2025 and up to 40% by 2035 (ASEAN Centre for Energy (2022)). The share of renewables in Malaysia's primary energy supply is only approximately 7.2% currently, mainly driven by hydrogeneration with a small share of solar energy (Suruhanjaya Tenaga 2021). As part of its Low Carbon Nation Aspiration 2040 (LCNA 2040), Malaysia aspires to increase the share of renewables in the total primary energy supply to 17% by 2040 (Economic Planning Unit-PMD 2022; Free Malaysia Today (FMT) 2022). Under the LCNA 2040, it is also targeting a hydrogen economy with aspirations to implement pilots and develop market entry programs under the Fourteenth and Fifteenth Plans (2031–2040). This includes plans to develop the region of Sarawak as a globally competitive hydrogen export hub (Economic Planning Unit-PMD 2022).

Malaysia, recognizing the importance of hydrogen as a low-carbon fuel for powering the future sustainable growth of the economy, has been developing its hydrogen economy for several decades (Malaysian Investment Development Authority 2020). The first national Solar, Hydrogen, and Fuel Cells Roadmap for Malaysia was published in 2006 by the Malaysian Center of Green Technology and Climate Change (formally Pusat Tenaga Malaysia) under the Ninth Malaysia

Plan. However, there was no follow-through on this in subsequent plans (Economic Planning Unit, Prime Minister's Department 2006; Academy of Sciences Malaysia 2020). In 2017, the Academy of Science Malaysia published the Blueprint for Fuel Cell and Hydrogen Industries in Malaysia, which substantially updated the Solar, Hydrogen, and Fuel Cells Roadmap and proposed a new direction (Academy of Sciences Malaysia 2020). The Sustainable Energy Development Authority is responsible for developing hydrogen and renewable energy options under the Renewable Energy Act of 2011. Malaysia's R&D efforts include a solar/hydrogen eco-house project based on proton exchange membrane fuel cell technology (Universiti Kebangsaan Malaysia) and the development of fuel cell tricycles, scooters, and cars (Universiti Teknologi Malaysia) (Saidi 2005). It has also established a roadmap for developing codes and standards for hydrogen to facilitate its large-scale adoption (Academy of Sciences Malaysia 2020; Malaysian Communications and Multimedia Commission 2020). The state-owned utilities company, Sarawak Energy, commissioned the country's first integrated hydrogen production plant and refueling station to serve hydrogen-powered vehicles (Pim 2019).

Japanese companies have been actively exploring opportunities related to hydrogen and other decarbonization in Malaysia. Malaysia's SEDC Energy, Eneos, and Sumitomo signed an MoU to explore the development of a green hydrogen supply chain in Sarawak, Malaysia, and Japan (Kumagai, Japan's ENEOS, Sumitomo, Malaysian SEDC Energy mull green hydrogen supply network 2020). Malaysia's state-owned energy companies Petroliam Nasional (Petronas) and Eneos are exploring opportunities for commercial hydrogen production and conversion into MCH as part of the development of a clean hydrogen supply chain between Malaysia and Japan (Petronas 2022). Petronas has also engaged with the Japan Bank for International Cooperation to explore investment opportunities in hydrogen, ammonia, renewable energy, and carbon capture and storage (Ellis 2022). Petronas, Sumitomo Corporation, and Tokyo Gas Co. Ltd are also collaborating to build a supply chain to deliver carbon-neutral methane (produced using methanation and green hydrogen) to Japan (Sumitomo Corporation 2021; Tokyo Gas 2021). Petronas, which announced its plans to achieve net-zero emissions by 2050, has worked with international partners to explore opportunities for collaboration with regard to green hydrogen (Chu 2020). South Korea is also active in Malaysia, with the SK Group partnering with the Petronas subsidiary Gentari to explore opportunities related to hydrogen across mobility, advanced materials, and carbon capture and storage (Hydrogen Central 2022b). Other South Korean companies such as Samsung Engineering, POSCO, and Lotte Chemicals have signed an MoU with the Sarawak Energy and Sarawak Economic Development Corporation to collaborate on the H2biscus green hydrogen/ammonia project in Sarawak (Battersby 2022a). The H2biscus Project is positioned to support the development of Sarawak as a globally competitive green hydrogen/ammonia export hub (Battersby 2022b; Malaysian Investment Development Authority 2021).

The Philippines

The Philippines is the fourth-largest economy in the ASEAN region, with a GDP of $393.6 billion (IMF 2022). However, it is the second-largest country in terms of population, after Indonesia, with a population of approximately 110 million people. Fossil fuels account for approximately 65.2% of its primary energy supply (IEA 2021; Department of Energy 2021), with renewables, led by geothermal, constituting the remainder (34.2%). The Philippines has ambitious climate targets despite its heavy dependence on imported fossil fuels. Although it has not set net-zero targets yet, it plans to achieve a 35% share of renewables in the energy mix by 2030 and a 50% share by 2040 (Wartsila 2022). The Philippines has not published a specific hydrogen policy; however, the government has been actively exploring the possibility of alternative clean fuels as part of its national energy plan. In November 2020, the Department of Energy issued a special order directing the creation of a Hydrogen and Fusion Energy Committee to conduct a "Study on Hydrogen and Fusion Energy including Infrastructure Development Methods and Strategies" (Department of Energy 2021). This study explored scenarios across power and transport applications. Hydrogen production methods using coal, natural gas, renewables, and nuclear energy have also been considered. The Department of Energy has worked hard to develop collaborations and partnerships to leverage the opportunities arising from the hydrogen economy (Department of Energy 2021).

In 2018, Toshiba Energy Systems & Solutions Corporation and National Electrification Administration of the Philippines, with support from the METI, agreed an MoU for implementing H2One, the renewable-based off-grid solution (Toshiba Energy Systems & Solutions Corporation 2018). In 2021, the Department of Energy reached an MoU with the Australian R&D firm Star Scientific Ltd to explore the potential of hydrogen as a clean energy source for the Philippines (Reuters 2021). Under the MoU, Star Scientific will use its Hydrogen Energy Release Optimizer system to convert coal-fired power plants to green hydrogen production facilities. To boost hydrogen development, the Department of Energy signed an MoU with Japan's Hydrogen Technology Inc. to explore the potential for hydrogen production in the Philippines (Crismundo 2021). Japan's interest and investment in the use of hydrogen/ammonia, as a decarbonization tool, extend to the power sector, where the Japanese power utility Jera has acquired a substantial stake in the Aboitiz Power Corporation. Jera aspires to burn hydrogen and ammonia in Aboitiz's gas and coal plants, respectively, thus taking the initiative to decarbonize the Philippines' power sector (Tsukimori 2022).

Singapore

Singapore, with a GDP of $396 billion, is the third-largest economy in the ASEAN region and is among the richest ASEAN member states (IMF 2022). Singapore's primary energy supply is dominated by imported fossil fuels, with natural gas accounting for almost 95% (Energy Market Authority 2022a; IEA 2021). As part of its commitment to reach net-zero by or around mid-century, Singapore plans to limit emissions to approximately 60 million tons of CO_2 by 2030 (National Climate Change Secretariat 2022). Given its lack of domestic natural resources, it has developed frameworks and strategies to tackle climate change and decarbonize its economy. For example, it implemented a carbon tax in 2022 to help meet its energy transition targets (Loh 2022). As part of its efforts, Singapore developed its National Climate Change Strategy in 2012, followed by the Sustainable Singapore Blueprint in 2015 and Singapore Climate Action Plan in 2016. Three years later, Singapore's Energy Market Authority announced the Future of Singapore's Energy Story and established decarbonization plans for the electricity sector. Hydrogen, along with natural gas, solar coupled with energy storage systems, and interconnected regional power grids, will be used in a future where energy is reliable and produced and consumed efficiently (Energy Market Authority 2019).

Singapore's LTS focuses on transforming its economy by harnessing emerging technologies and leveraging international collaborations (National Climate Change Secretariat 2020). In 2020, Singapore concluded a study commissioned by the National Climate Change Secretariat of the Prime Minister's Office on hydrogen imports and downstream applications jointly conducted by KBR Inc. and Argus (KBR Inc. 2021). The techno-economic assessment covered five sectors for downstream applications: power generation, industrial and manufacturing, mobility, non-industrial gas, maritime, and ports. In 2021, Singapore launched the Low Carbon Energy Research Funding Initiative. This program, administered by the Agency for Science, Technology, and Research, focuses on hydrogen and CCUS-related technologies for downstream applications in the power, industry, and transport sectors (Agency for Science, Technology and Research (A*STAR) 2021). In addition, Shell has partnered with SembCorp Marine Ltd and its wholly owned subsidiary LMG Marin AS to trial hydrogen fuel cell ships in Singapore (Shell 2021).

In 2021, the Singapore government released the Green Plan 2030, in which hydrogen plays an essential role in achieving the country's energy and climate objectives in the mid to long term (Government of Singapore 2021). In March 2022, the Energy Market Authority commissioned the Energy 2050 Committee to develop recommendations for the decarbonization of the electricity sector. This committee reported findings that will help shape the potential of using hydrogen as a critical component of the energy mix by 2050 (Energy Market Authority 2022b).

Singapore's National Hydrogen Strategy, launched in October 2022, developed its vision of low-carbon hydrogen as a critical pathway to further the decarbonization transition toward the 2050 net-zero goal (Ministry of Trade and Industry 2022). This is the first hydrogen strategy in the ASEAN region, and its target is to provide energy security and strengthen the island state's resilience. The deployment of land-intensive renewable sources to generate clean energy is a major challenge for the island. Singapore's Solar Energy Research Institute has developed a solar photovoltaic roadmap that estimates a peak potential deployment of 8.6 GW, meeting approximately 10% of Singapore's 2050 electricity demand. Hence, clean hydrogen is produced regionally and then imported, which can then be used to generate electricity, initially using a blend with natural gas and later using only hydrogen. This could help meet almost 50% of the projected electricity demand by 2050. Clean hydrogen would also help decarbonize Singapore's extensive industrial, refining, and chemical sectors. Singapore's geographical location makes it a key part of global supply chains, a major global maritime bunkering hub, and a key aviation hub for regional and international connectivity. However, its crude refining (world's fifth-largest refining export hub) and chemical industry is emissions-intensive, and hydrogen could help decarbonize the sector. Hydrogen could also be used in the maritime sector in alignment with the Maritime Singapore Decarbonization Blueprint launched in 2022. The blueprint outlines Singapore's approach to using clean fuels such as hydrogen, ammonia, and other derived synthetic fuels in the maritime sector. Singapore's aviation sector could also benefit from the introduction of hydrogen-derived sustainable aviation fuels and chemicals.

Singapore's hydrogen strategy also focuses on international collaboration to develop supply chains for low-carbon hydrogen, which means that it has actively engaged in regional and global outreach to build such relationships. Since 2021, Singapore has entered into a range of agreements with New Zealand, Australia, Chile, Malaysia, Cambodia, Laos, Vietnam, Brunei, China, India, Indonesia, and Colombia. These agreements focus on a variety of engagements, including the development of low-carbon hydrogen solutions, carbon markets, carbon capture and storage, carbon credits, renewable energy electricity trade, and regional electricity grids. Singapore has also signed an MoU with Saudi Arabia focusing on renewable energy and hydrogen technologies, along with the development of a circular carbon economy (Arab News 2021). In January 2022, Singapore's Ministry of Trade and Industry and Japan's METI signed an MoU for cooperation on low-emission solutions, including hydrogen (Ministry of Trade and Industry Singapore 2022).

Singapore is an early mover in the hydrogen economy, with several entities seeking to explore opportunities for collaborations with international companies. In 2020, two Japanese companies, Chiyoda and Mitsubishi, and five Singapore companies, PSA Corporation, Jurong Port Pte Ltd, City Gas Pte Ltd, Sembcorp Industries, and Singapore LNG Corporation Pte Ltd, entered into an MoU. This agreement was for the joint R&D of technologies related to the importation, transportation, and storage of hydrogen (Reuters 2020). In 2021, Itochu Enex, Vopak Singapore, Pavilion Energy Singapore, Mitsui O.S.K. Lines, and Total Marine announced an MoU on a joint study on using ammonia as a marine fuel option in the Port of Singapore (Itochu 2021). Singapore's Keppel Data Centers, along with Kawasaki Heavy Industries Ltd, Linde Singapore, Mitsui O.S.K. Lines, and Vopak, also announced an MoU to explore the development of the supply infrastructure required to import LH into Singapore to power the Keppel data center (Vopak 2021). In August 2022, Keppel Infrastructure announced plans to work with Mitsubishi and Jurong Engineering to build a power plant that can run on natural gas and a blend of 30% hydrogen. It is also running a feasibility study with Mitsubishi to explore the development of an ammonia-fueled power plant. These projects will all help Singapore decarbonize its power sector as it seeks to achieve its net-zero ambitions (Ang 2022).

In summary, Singapore, with its strong international relationships, a competitive domestic industry, efficient financial markets, and strong research centers, is well placed to take advantage of the nascent hydrogen economy evolving in the region.

Thailand

Thailand is the second-largest economy in the ASEAN region, with a GDP of $513.16 billion in 2021; it is ranked fourth in terms of population, with a population of 70 million (IMF 2022). Fossil fuels account for approximately 80% of the primary energy supply in Thailand (IEA 2021). Biofuels and waste primarily supply 20%, with marginal contributions from hydropower and other renewables. As part of its net-zero ambitions, Thailand has targeted achieving carbon neutrality by 2050 and net-zero emissions by 2065 (ASEAN Centre for Energy (2022)). It plans to increase the share of renewables in its total final energy consumption from 14% to 30% by 2037 and in its electricity generation capacity mix from 14.9% to 50% (Meseroll, Chumroentaweesup and Chanchao 2022; Office of Natural resources and Environment Policy and Planning 2022). The targets increase to 68% of total electricity generation by 2040 and 74% by 2050. In the 10-year Alternative Energy Development Plan[7] (2012–2021), Thailand plans to produce hydrogen from renewable energy resources and use it for energy storage (Department of Alternative Energy Development and Efficiency 2011). As part of the updated 20-year Alternative Energy Development Plan (2018–2037), hydrogen is included as an alternative fuel, with a target consumption of 3,500 tons by 2036. The Electricity Regulatory Commission has also included hydrogen in its renewable energy purchase portfolio, enabling its integration into electricity generation. Although Thailand has not yet developed a national hydrogen strategy, it has been developing hydrogen applications for the past decade. In 2018, the Electricity Generating Authority of Thailand (EGAT) started to develop a prototype of an integrated wind/hydrogen system at the Lam Takhong Wind Turbine Phase 2 Project to better utilize intermittent renewable energy resources (Dogaojo 2020). Further, Thailand has stated that it will only sell battery electric vehicles and hydrogen fuel cell vehicles after 2035 to decarbonize the transport sector (Randall 2021). The Thai National Oil Company, PTT Public Company, PTT Oil and Retail Business Plc, Toyota Motor Corp., and Bangkok Industrial Gas Company launched Thailand's first HRS in Pattaya in late 2022 (Apisitniran 2022). Moreover, the Thailand Board of Investment, as part of its 2023–2027 Investment Promotion Strategy, has announced investment incentive programs supporting the manufacture of hydrogen vehicles and incentivizing clean hydrogen and ammonia production for power and steam generation (Thailand Board of Investment 2022).

Japan has worked with Thailand to develop and support its hydrogen economy; a memorandum of cooperation between the METI and Thailand's Ministry of Energy was signed in early 2022 (METI 2022). As part of the memorandum, Japanese and Thai companies, including Mitsubishi Heavy Industries, Hitachi, Toshiba, and Toyota Motors, are exploring collaboration opportunities with the Thai coal mining companies, Banpu and EGAT (Muramatsu 2022). Jera and the Thai power producer Electricity Generating Public Company have also agreed to collaborate to build hydrogen and ammonia supply chains in Thailand. Moreover, Saudi Arabia has engaged with Thailand in hydrogen production, and Aramco is exploring opportunities for collaboration with PTT. In May 2022, Aramco and PTT signed an MoU to explore collaboration opportunities related to blue and green hydrogen among other clean energy initiatives such as carbon capture and electric vehicles. The MoU focuses primarily on increasing the supply of crude oil, petrochemical products, and LNG to Thailand. Thailand is a net importer of crude and petroleum products, and it also sources natural gas as LNG through pipelines from Myanmar. In 2021, Saudi Arabia was the second-largest supplier of crude oil to Thailand, with the United Arab Emirates being the largest (Aramco 2022; Muramatsu, Saudi Aramco boosts oil exports to Thailand in PTT deal 2022; SPA 2022). PTT has also been increasingly active in the hydrogen space, buying a stake in the Indian renewable energy company Avaada Energy in 2021. Avaada Energy, which operates renewable energy plants in India, has announced a $5 billion, 1 million ton clean ammonia project in Rajasthan (Phoonphongphiphat 2021; Singh 2022a, 2022b). Thai companies such as Thai Oil Plc, the ATE Company, EGAT, and the Electricity Generating Public Company have also started to explore international opportunities, with Thai Oil buying a stake in the US-based clean hydrogen company Versogen. Further, the ATE Company, EGAT, and the Electricity Generating Public Company are exploring investment opportunities with regard to fuel cells and electrolyzers with Bloom Energy Company (EGAT 2021; Praiwan 2022).

Cambodia, Laos, Myanmar, and Vietnam

Cambodia, Laos, Myanmar, and Vietnam collectively represent approximately one-quarter of the ASEAN population and approximately 15% of the regional GDP. These countries also have a varied mix of energy supply; however, all are dependent on fossil fuels (IEA 2021). Despite such dependencies, all have set targets for net-zero emissions by 2050, either with or without conditions (ASEAN Centre for Energy (2022)). In addition, they are all targeting an increase in the share of renewables in their energy mix to meet their net-zero ambitions. Table 12.1 provides the details of these targets.

TABLE 12.1 Renewable energy targets of Cambodia, Laos, Myanmar, and Vietnam

Country	*Ambitions and aspirations*
Cambodia	The ambition is to increase the share of renewables (solar, wind, hydro, and biomass) in the energy mix in terms of generation capacity by 25% by 2030.
Laos	The ambition is to increase the share of renewables in total energy consumption by 30% by 2025. Target a hydroelectric capacity of 13 GW by 2030.
Myanmar	The ambition is to increase the share of renewable energy in electricity generation to 39% by 2030.
Vietnam	The ambition is to increase the share of renewables in power generation by 32% by 2030 and by 43% by 2050.

Source: ASEAN Centre for Energy (2022).

However, the focus on hydrogen production is uneven across these countries because of their economic status and relative lack of industrial development and capacity. Cambodia has explored hydrogen as a potential decarbonization alternative to natural gas for its transport and power generation sectors (National Council for Sustainable Development 2021). As part of its Renewable Energy Development Strategy, Laos has explored the potential use of hydrogen as an alternative fuel (Government of Laos 2011; UN Climate Technology Center and Network 2020). Vietnam, as part of its National Green Growth Strategy for 2021–2030 Vision to 2050, has focused on transitioning to a low-carbon economy as well as providing incentives to develop hydrogen (Foster and Taylor 2022; Grantham Research Institute 2021; VietNamnet 2021). It also aspires to use green hydrogen and green ammonia to produce electricity by co-firing with natural gas and coal, respectively (Ali 2022; Quynh 2021). Myanmar is yet to develop a hydrogen strategy roadmap.

However, a number of companies in these countries are actively exploring business opportunities. The Vietnam Oil and Gas Group (PetroVietnam) has initiated research and feasibility projects to explore clean hydrogen production (FuelCellsWorks 2021). Hydro gene De France SA and Pestech International Berhad, the Malaysian electrical engineering company, have signed an MoU to collaborate on clean hydrogen production using hydroelectricity in Cambodia and Malaysia (Ingram 2022). Pestech plans to develop hydrogen fuel cells for other applications in Cambodia (Pestech 2022). The Green Solution Group could invest up to $840 million in developing a plant that produces 24,000 tons of clean hydrogen, 150,000 tons of ammonia, and 150,000 tons of oxygen annually. The plant, which is expected to be completed by 2024, includes a collaboration between Thyssenkrupp and Black and Veatch (Black & Veatch 2022; CPA Corp 2022; Reuters 2022). The Green Solution Group has also started working with the Norwegian company ECONNECT Energy to export clean ammonia to the markets of Japan and South

Korea. Finally, South Korea's SK Energy has announced its interest in exploring clean hydrogen production in Vietnam as part of the Mekong Delta Master Plan (Hydrogen Central 2022c).

ASEAN's strategic considerations regarding hydrogen

A young population, strong economic growth, and an increase in the standard of living in ASEAN countries have led to a significant rise in energy consumption (Invest in ASEAN 2023). Electricity generation has almost tripled over recent decades (ASEAN Centre for Energy (2022)). This demand has been met predominantly by the expansion of the energy capacity based almost completely on fossil fuels. This has also resulted in an increasing dependency on energy imports, and recent events in Europe have brought the issue of energy security to the fore. Increased fossil fuel usage has raised air quality and pollution concerns in rapidly urbanizing ASEAN countries. While the majority of ASEAN countries have set net-zero targets, they face the challenge of securing a sustainable energy solution to meet their growing energy demand while managing their increasing emissions.

The ASEAN region has substantial renewable resources for supporting the transition to cleaner and more sustainable forms of energy. Renewable capacity can then be used to develop a clean hydrogen economy in the region, thereby addressing energy security and air quality concerns. The strong dependence on fossil energy makes ASEAN member states a suitable case study for considering hydrogen as a low-carbon energy option to diversify the fuel mix. Given the uneven distribution of fossil and renewable energy sources and access to advanced technologies, collaboration among ASEAN member states is a sensible approach for successful hydrogen development in the region.

This region also has the requisite industrial capacity, technical capability, and resources to manage the entire hydrogen value chain from production to end-use applications. Research institutions can support the energy transition by developing new and innovative technologies. Over recent years, the policy and regulatory environment in the ASEAN region has also transitioned to a much more supportive framework, enabling the development of hydrogen hubs and facilitating investment in the related infrastructure.

With its existing investments in gray hydrogen-producing infrastructure and associated know-how, the ASEAN region is well placed to leverage these strengths with ongoing investment and the development of CCUS technologies and pilots (IEA 2022; Suwanto, Lenanto and Suryadi 2022). These CCUS pilots could help the ASEAN region develop its blue hydrogen economy once renewable energy capacity has been adequately scaled up. Increasing the renewable energy share, adopting carbon pricing and related instruments, investing in CCUS pilots, and using hydrogen to decarbonize transport and other hard-to-abate sectors will be critical to ensure continued transition to meet the region's net-zero ambitions.

Japan has established a strong presence in the ASEAN region over time and maintains a keen interest in the joint development of the hydrogen economy in collaboration with member states. Historically, the region has primarily imported energy from Japan, and the country has sought to secure these markets for its export products such as automobiles and white goods. It has invested extensively in the region, supporting the energy infrastructure such as power plants, LNG terminals, and refineries. The country has also supported the development of sustainable technology such as geothermal energy in the ASEAN region. In the short term, collaboration with Japanese companies at the forefront of hydrogen technology development and demonstration represents a strategic opportunity for ASEAN member states. In the long term, ASEAN members will need to constantly evaluate the evolving energy circumstances and economic development domestically to ensure a sustainable hydrogen economy.

India

India is the world's second-largest country in terms of population (1.4 billion) and the fifth-largest economy, with a GDP of $3.17 trillion (IMF 2022). As befits a growing economy and a population with rising per capita incomes and living standards, India is the third-largest energy consumer globally. It is also the third-highest emitter of greenhouse gases, as India's energy consumption is predominantly fossil fuel-based. Despite such high energy consumption and related emissions, India's per capita consumption of energy and emissions is less than half the global average (IEA 2021). Over the coming decades, India's energy consumption is expected to increase substantially as the country urbanizes and its economy grows. The resultant increase in energy consumption is expected to make India one of the largest global energy importers, with crude oil and gas being key fuels. This dependency on imported fuels, especially crude oil, poses major energy security challenges for policymakers. India has been trying to develop alternative sources of energy to mitigate external supply and price volatility risks. As part of this push, it has expanded its non-fossil fuel share in the electricity mix with investments in renewables such as solar, wind, and hydro as well as its nuclear capacity, in line with its commitment to reach net-zero by 2070 (Press Information Bureau 2022).

Historically, petroleum has been the single largest import commodity for India, and the high price of imported oil has always been a fiscal concern. India consumes more than 4 million barrels of petroleum per day. Of these, approximately 40% are diesel and 15% are petrol. Diesel is mainly consumed by heavy trucks and tractors (agricultural usage), whereas petrol is used by passenger cars and two-wheeled vehicles. When oil prices rise, as they did in 2004–2008, so does the search for alternatives. Unsurprisingly, hydrogen first emerged as a fuel option during the 2004–2008 oil price boom. India released its National Hydrogen Energy Road Map prepared by the National Hydrogen Energy Board in 2006[8] (Government of India 2006). Research institutions, oil companies, and automotive companies have investigated hydrogen as a fuel source (Lok Sabha 2008). However, this initiative did not progress because of the lack of non-fossil fuel hydrogen sources, and interest waned as oil prices fell in 2008 during the global financial crisis. However, this was not a one-time event. Even in the 1970s, Indian policymakers and energy planners sought to allocate research resources to lead acid battery-powered vehicles and develop fuel cells based on technologies such as sodium sulfur, metal air, hydrogen peroxide, and lithium-based fuel cells (Planning Commission 1974). However, this interest declined over the next few decades as the effects of the shock gradually subsided.

On August 15, 2021, India's 75th Independence Day, Prime Minister Narendra Modi announced the National Green Hydrogen Mission. One of its objectives is to make India a global hub for green hydrogen production (Press Information Bureau 2021). In 2021, India launched its Hydrogen Energy Mission to produce hydrogen from renewable energy (Government of India 2022). Subsequently, the Ministry of Power released the Green Hydrogen Policy with the goal of producing 5 million tons of clean hydrogen by 2030 (Press Information Bureau 2022).

Hydrogen is already used on a large scale in India for petroleum refining, fertilization (urea), and steel manufacturing. India's annual demand for hydrogen, primarily gray hydrogen, is approximately 6.7 million tons. The country has a crude refining capacity of over 250 million tons and is the second-largest steel producer, with an annual crude steel production of over 100 million tons. The fertilizer sector is critical because of its importance in agriculture. Among the three aforementioned sectors, petroleum refining is the most likely candidate for shifting to clean hydrogen and will help manage the carbon footprint. Most Indian refineries generate hydrogen in-house from petroleum or natural gas where available. If clean hydrogen becomes available, it will compete with either naphtha or LNG in terms of price. Several Indian refineries have announced both green and blue hydrogen plans coupled with CCUS to reduce emissions (Bhatt, Kamboj, and Roychoudhury 2023). The state-run Indian Oil plans to build India's first clean hydrogen plant at its petroleum refinery in Mathura (Heynes 2021). In 2021, Reliance Industries Limited announced that it would build a gigafactory to manufacture electrolyzers for clean hydrogen. The company also proposed building a gigafactory to manufacture fuel cells (Reliance Industries Limited 2021). Reliance is a significant exporter of refined petroleum products and may be more sensitive to the international pressure on global oil majors to reduce their carbon footprints.

The steel industry is also beginning to consider clean hydrogen as a decarbonization option. The Indian steelmaker Tata Steel is planning to set up a 100-MW clean hydrogen plant at one of its operations in the Netherlands (Tata Steel Europe 2021). JSW Green Energy, a subsidiary of JSW Energy, recently signed an agreement with Fortescue Future Energies to collaborate on clean hydrogen production, green steelmaking, and hydrogen mobility applications. The Ministry of Power announced plans in July 2021 to introduce Green Hydrogen Consumption Obligations in fertilizer production and petroleum refining, where such industries will be mandated to use clean hydrogen as a part of their energy consumption (Bhaskar 2021).

Currently, most of the push for decarbonizing transport is focused on electric vehicles. However, this approach has several limitations. First, approximately 75% of India's electricity is generated using coal; therefore, electric vehicles run on coal rather than oil. Second, electric vehicles target only 15% of the petroleum market. Shifting heavy trucks to electric trucks (40% of oil demand) is technically and financially implausible for India given its resource constraints. Third, electric batteries require substantial quantities of lithium and cobalt; both are imported and have vulnerable supply chains, which is less of an issue for hydrogen-powered FCEVs. Finally, hydrogen generation using renewable electricity can help address the intermittency of renewable energy.

Hydrogen mobility applications in India are currently restricted to small pilot projects, many of which are at the proposal stage. However, the regulatory framework for using hydrogen as a fuel is already in place, with the Ministry of Road Transport and Highways having approved the use of hydrogen for automotive applications in 2016, followed by additional approval requirements for hydrogen fuel cell vehicles in 2020. A fleet of 50 buses in the national capital New Delhi runs on compressed natural gas blended with hydrogen. The state-owned power utility NTPC has proposed two pilot mobility projects in New Delhi and Ladakh. Both involve five cars and five buses running on hydrogen (NTPC 2021). NTPC has also signed an MoU with Siemens to collaborate on hydrogen production using renewable energy for mobility-focused applications. Multiple research institutes across India are exploring hydrogen applications across mobility, industry, chemical feedstock, and fuel cells, along with conducting research on electrolyzer development (Department of Science and Technology 2020).

With the direction provided by the government, Indian companies have been able to quickly develop collaborations across the hydrogen value chain, including plans to manufacture electrolyzers domestically with partners overseas. Larger companies have formed alliances such as the Indian Hydrogen Alliance, established in 2021 with Reliance Industries, Chart Industries, and JSW Steel as core members. The Hydrogen Association of India, established in 2009, also participates in state-owned enterprises. Both groups are working to help policymakers develop India's hydrogen economy. Ohmium International has built a plant in India to manufacture PEM electrolyzers with an annual capacity of 0.5 GW. The Adani Group is also planning to build three gigafactories to manufacture solar modules, electrolyzers, and wind turbines. India has seen sustained interest in electrolyzer manufacturing with partnerships such as Reliance–Stiesdal, H2e Power, GreenkoZeroC–John Cockerill, Ohmium, Larsen & Toubro–HydrogenPro, and ACME–Sweden Scatec ASA among the prominent ones. Indian companies have also ventured overseas to develop clean hydrogen projects; for example, ACME Solar has developed a project in Duqm, Oman (ACME 2021). India's ambition to become a key global hydrogen hub has led the country to develop global relationships focused on clean hydrogen and renewable energy, including with the United Kingdom, the United States, France, Japan, Germany, Australia, Italy, Saudi Arabia, Bahrain, and Uzbekistan (Delaval et al. 2022).

While India has ambitions to be an export hub for clean hydrogen, its domestic demand is expected to reach 9 million tons (Giri 2022). To become a surplus producer and potential exporter, India must invest in renewable capacity and expand its electrolyzer manufacturing base to meet this demand. While the government is enticing overseas electrolyzer manufacturers to invest in manufacturing capacity in India through production-linked incentives,[9] demand and pricing issues remain (Baruah 2022; Krümpelmann 2022). The use of clean hydrogen produced from renewable power sources can help India reduce emissions from the transportation sector and address the intermittency of renewable energy. However, this shift toward new energy sources requires investment in technology and infrastructure as well as regulatory support.

Case study

The case studies discussed in this section focus on two supply chains. One supply chain involves blue ammonia for co-firing in Japan's coal-fired power plants, whereas the other uses MCH as a vector to transport hydrogen for co-firing in a gas-fired power plant. Both case studies highlight the solutions that Japan is exploring to decarbonize its power-generation assets. These supply chains also highlight the sharing and development of skills and knowledge for handling and monitoring these fuels for their end use. Both case studies involve the participation of a conglomerate of Japanese entities across shipping, chemical, power generation, engineering, and trading houses. The case studies also highlight the close cooperation between Japan and other countries, with two objectives. The first is to help develop the hydrogen supply chain-related infrastructure through technological development and cooperation and the second is to develop an international hydrogen market in pursuit of Japan's energy needs.

Blue ammonia demonstration between Saudi Arabia and Japan

In September 2020, the Saudi Arabian Oil Company (Saudi Aramco) and Institute of Energy Economics in Japan demonstrated the production and shipment of blue ammonia from Saudi Arabia to Japan. This was aided by a partnership with the Saudi Basic Industries Corporation (SABIC) as well as support from the METI (METI 2021). The Mitsubishi Corporation, JGC Corporation, Mitsubishi Heavy Industries Engineering Ltd, Mitsubishi Shipbuilding Co. Ltd, and UBE Industries Ltd also supported the demonstration (The Institute of Energy Economics (IEEJ) 2020). This demonstration project was conducted based on the MoU between Saudi Arabia and Japan signed earlier in Tokyo during the Saudi Vision 2030 Business Forum (Aramco 2019). This MoU was intended to explore the potential use of hydrogen and ammonia for decarbonizing the Japanese energy system, while ensuring fossil fuel resources continued to be used effectively. From Saudi Arabia's perspective, building a hydrogen supply chain to Japan validates the potential long-term export of fossil fuels in a decarbonized manner, especially through carbon capture and storage. It also provides the Kingdom with valuable experience in understanding the entire CO_2 chain; testing CO_2 monitoring and surveillance techniques; and tracking, mapping, and measuring the injected CO_2. These are all critical to the success of the circular carbon economy[10] framework (Al Khowaiter and Mufti 2021). This demonstration project, as the world's first international blue ammonia shipment project, is expected to be a driver for building a global hydrogen supply chain. Forty tons of high-grade blue ammonia has been transported to Japan for zero-carbon power generation. Figure 12.4 illustrates a conceptual flow diagram of the supply chain for blue ammonia from production in Saudi Arabia to its end use in Japan.

The supply chain includes the conversion of hydrocarbons (natural gas in this case) to hydrogen and ammonia and the capture of the associated CO_2 emissions. It overcomes the challenges associated with shipping blue ammonia to Japan for use in power plants, with 30 tons of CO_2 captured during the process designated for use in methanol production at SABIC's Ibn-Sina facility, and another 20 tons for enhanced oil recovery in Aramco's Uthmaniyah field (Shabaneh, Al Suwailem, and Roychoudhury 2020).

Ammonia was chosen as the hydrogen carrier for the demonstration project primarily because it is already traded as an international commodity with established shipping lines and protocols. Ammonia synthesis from natural gas is also a mature technology, with no need to reconvert ammonia into hydrogen because the end-use

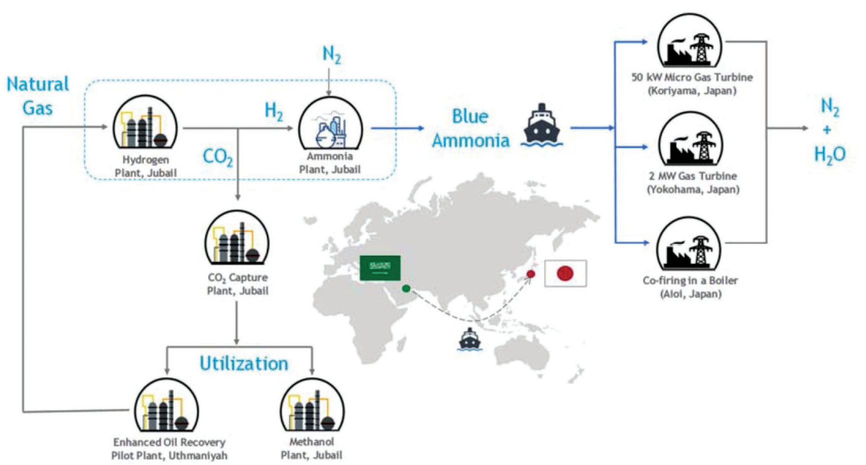

FIGURE 12.4 Blue ammonia supply chain.

Source: Institute of Energy Economics, Japan.

application is co-fired with coal-fired power generation. Ammonia is a promising fuel for power generation because the combustion characteristics of ammonia and pulverized coal are similar, which facilitates co-firing. Co-firing with coal for power generation is an important part of Japan's attempts to decarbonize its power sector. The share of coal in power generation in Japan is expected to reduce to 19% by 2030 from approximately 26.5% in 2021. This shows the continued role of coal in the Japanese power generation mix and, hence, the pressure to reduce emissions in the sector to the extent possible (ISEP 2022; METI 2021). Blue ammonia also enables Japan to gradually transition its power sector to 100% ammonia firing from initial co-firing with coal. In the mid and long term, hydrogen will be required for applications other than coal-fired power generation, such as gas-fired power generation, as well as in the transport and industrial sectors. Thus, technological development is necessary for ammonia cracking into hydrogen, while other hydrogen carriers such as LH and LOHC systems are required to enter the commercial stage for hydrogen transport.

After the successful validation of the hydrogen supply chain from Saudi Arabia, Japan conducted other hydrogen supply pilots with the United Arab Emirates, with end-use applications in Japan's refining and petrochemical, power generation, and fertilizer sectors (Saadi 2021a, 2021b; Saadi and Kumagai 2021a). In 2021, Japan's largest refiner, Eneos, announced the signing of an MoU with Aramco, focusing on feasibility studies to explore the development of clean hydrogen and ammonia supply chains (Kumagai 2021). In October 2022, the Japan Oil, Gas, and Metals National Corporation announced a memorandum of cooperation with Aramco focusing on the production and storage of low-carbon hydrogen and fuel ammonia (Jogmec 2022). Saudi Arabia is a key energy supplier and an important trade partner for Japan. This is reflected in the multiple areas of collaboration that both countries are working on, including health, finance, wastewater management, and investments.

MCH demonstration between Brunei and Japan

In June 2020, the AHEAD announced the successful completion of a pilot project to supply hydrogen to Brunei using MCH. This project was financially supported by NEDO, along with cooperation from the Brunei government and TOA Oil Company. The demonstration supply chain pilot involved coordination, collaboration, and cooperation across multiple corporate and administrative entities, both in Brunei and Japan. Hence, it is a great example of Japan's investments overseas securing hydrogen resources for its domestic economy, aligned with Japan's Strategic Road Map for Hydrogen and Fuel Cells. As part of the pilot Global Hydrogen Supply Chain Demonstration Project, the AHEAD financed the construction of a hydrogenation demonstration plant at Sungai Liang Industrial Park in Belait District, Brunei. The construction of the plant began in April 2018 and was completed in September 2019 (Lim 2019). The hydrogenation plant uses hydrogen produced from LNG sourced from the Brunei LNG Sdn Bhd plant (Brunei LNG[11]). Hydrogen was produced via steam methane reforming using the organic chemical hydride method. The LH is converted into MCH, a stable compound that can be shipped by commercial vessels at ambient temperature and pressure.

The pilot shipment of MCH from Muara Port, Brunei, to Kawasaki, Japan, needed five ISO tank containers, each with a capacity of 24 kiloliters and weighing 4.7 tons overall. The project plans to supply 210 metric tons annually to Japan. The shipped MCH is separated into hydrogen and toluene at a dehydrogenation plant at the Keihn Refinery, Kawasaki. Hydrogen is blended with the byproduct gas from the refiner and used as fuel in the gas turbines at the Mizue Thermal Power Plant of Toa Oil Co. for power generation (Kumagai 2020b; The Star 2020). The separated toluene is then transported back to Brunei Darussalam for hydrogen binding. The objective of this project is to explore opportunities to reduce the carbon footprint, enable the decarbonization of refinery operations, and validate Chiyoda Corporation's SPERA MCH technology (Chiyoda Corporation 2017, 2021a).

Following the successful demonstration of the pilot, Chiyoda Corporation, Mitsubishi Corporation, Mitsui & Co. Ltd, and Nippon Yusen Kabushiki Kaisha signed an agreement with Eneos Corporation. This agreement involves supplying hydrogen produced in Brunei through the MCH mechanism for use in Eneos' refinery decarbonization trials. Eneos' decarbonization trials (using 10,000-DWT chemical tankers for shipment) will be funded by the Consortium for Resilient Oil Supply. The refinery trials (at the Kawasaki, Wakayama, and Mizushima refineries) will focus on replacing the gray hydrogen used in refineries for the desulfurization of crude oil with hydrogen sourced from Brunei (Mitsui 2021; Nakashima 2021). This pilot study primarily aimed to validate the hydrogen supply chain, as the hydrogen produced was from natural gas without carbon capture. Future investment by Brunei in CCUS could enable the production of low-carbon hydrogen. With the launch of the Asia CCUS Network, Japan has been active in sharing knowledge on CCUS across the region (METI 2021; Rubrico 2021; Xinhua 2020b).

Conclusion

Japan needs hydrogen primarily to decarbonize its power generation sector and the rest of its industry to meet its climate goals. From the country's economic perspective, imported hydrogen must be cheap and available on scale. As part of its energy security requirements, Japan wants to import a multitude of diverse sources globally. In pursuit of this strategy, it has run hydrogen and ammonia pilots globally and collaborated to build hydrogen supply chains. Japan hopes to seed its companies and their proprietary technology in the as-yet-developing hydrogen economy to benefit from the expected rise in demand for clean and low-carbon fuels as part of its energy transition. However, it faces a conundrum. While it is trying to increase the attractiveness of hydrogen, its domestic industry remains comparatively hesitant, citing the high upfront costs and challenges of managing a new fuel supply chain.

By reaching all the major Asian economies, Japan is trying to secure stable hydrogen supply chains, use its financial heft to increase the attractiveness of its hydrogen technologies, and develop products based on hydrogen. It faces challenges in its approach. Potential suppliers in the region, such as Saudi Arabia, Australia, India, Gulf nations, and ASEAN member states, are also trying to develop a framework to leverage their existing technical and resource strengths. This will help them transition to a cleaner and more sustainable future without economic disruptions that challenge their progress. Japan hopes that the multiple pilots being run to create a sustainable hydrogen supply chain, thus creating a successful hydrogen economy domestically, will enable viable business models to evolve. For ASEAN member states, India, and Saudi Arabia, which are all seeking to develop their own hydrogen economies, engagement with Japan offers an opportunity to absorb the knowledge Japan has acquired through decades of experience. Engaging with Japan also offers access to a stable and secure market for clean hydrogen, providing a further opportunity to continue collaborating and cooperating.

In the Kingdom, Japan's potential hydrogen market will face challenges, as it will face competition from a multitude of sources. ASEAN member states, Australia, India, and other regional countries are interested in competing for a share of what could be a future high-growth sector. However, all these countries face constraints in their access to capital and technology (e.g., India and ASEAN countries), long transport routes (e.g., Australia, Saudi Arabia, and Chile), lack of domestic demand, and industrial capacity. The evolution of the hydrogen economy will generate additional challenges related to emission intensity for hydrogen production, certification requirements, and the imposition of sustainability metrics. Strategic partnerships, the validation of new and innovative business models, and increased coordination among regional stakeholders will help shape the evolution of the hydrogen economy.

Notes

1 The other nine themes were competitive industry, energy, entertainment & media, healthcare & medicals, quality infrastructure, agriculture & food security, SMEs & capability building, culture, sports & education, and investment & finance (MOFA 2017).
2 Authors' estimate, assuming a FCEV consumes 1,000 Nm^3 of hydrogen per year (10,000 km is the average annual driven mileage in Japan).
3 The ASEAN political and economic union was established in 1967 following the signing of the ASEAN Declaration by Indonesia, Malaysia, the Philippines, Singapore, and Thailand. These countries are referred to as the founding fathers of the ASEAN. The other five countries (Myanmar, Laos, Vietnam, Cambodia, and Brunei) in the 10-member group joined over time. ASEAN member states focus on regional intergovernmental cooperation and integration in economic, military, political, and other related aspects.
4 The ASEAN Energy Outlook baseline scenario projections focus on historical trends in energy consumption and supply and exclude the intervention of new policies. See https://aseanenergy.org/the-7th-asean-energy-outlook/.
5 The ASEAN Plan of Action for Energy Cooperation is a regional energy cooperation framework, aligned with the ambitions of the ASEAN economic community, focusing on improving energy security, accessibility, affordability, and sustainability within member states.
6 The National Research and Innovation Agency (Badan Riset dan Inovasi Nasional) was formed in 2021 by merging scientific research bodies. R&D in hydrogen has been

carried out since 2011 by the Agency for the Assessment and Application of Technology (Badan Pengkajian dan Penerapan Teknologi).

7 The draft National Energy Plan consists of five master energy plans: the Power Development Plan, Alternative Energy Development Plan, Energy Efficiency Plan, Gas Plan, and Oil Plan.

8 The National Hydrogen Energy Board was set up in 2003 under the Ministry of New and Renewable Energy, with the objective to prepare, implement, and monitor the National Hydrogen Energy Roadmap and National Hydrogen Energy and Fuel Cell Program (Press Information Bureau 2006).

9 Production-linked incentives have been created to attract investments in selected sectors to boost domestic manufacturing, increase investment scales, and incentivize exports. Sectors have specific incentives depending upon their requirements (Invest India 2020).

10 For a more detailed background on the circular carbon economy concept, see https://www.cceguide.org/guide/.

11 The AHEAD chose Brunei LNG for its pilot hydrogen supply chain demonstration project. The Brunei LNG plant, founded in 1969, was a pioneer in the Western Pacific in the large-scale liquefaction of natural gas and contributed to shaping the global LNG industry. The first LNG shipment from Brunei LNG, through a custom-built LNG carrier, the SS Gadinia, arrived in Japan in 1972. It marked the first long-distance ocean voyage in the Southeast Asian region to deliver LNG cargo to Japan, and this LNG infrastructure development and shipment model was later recreated in Indonesia, Malaysia, and Australia (Brunei LNG 2013). Brunei LNG is partly owned by Mitsubishi Corporation (25%), Shell Overseas Holding (25%), and the government of Brunei (50%) (Brunei LNG 1969; Mitsubishi Corporation 1969).

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13

ROLE OF HYDROGEN IN MEETING SOUTH KOREA'S ECONOMIC, ENVIRONMENTAL, AND STRATEGIC TARGETS

Jinsok Sung and Zlata Sergeeva

Introduction

Hydrogen has been used in South Korea for decades, including at petrochemical factories, in refineries, for electronics manufacturing (semiconductors, displays, LED, and photovoltaic applications), and in the transportation and food industries (Cigal 2016). Over 1.5 million tons of hydrogen is produced annually at petrochemical plants at Ulsan, Yeosu, and Daesan, mainly as a by-product, with most consumed by these production sites (Ministry of the Environment 2015). However, South Korea only started to develop its national plans to expand the hydrogen sector in 2005, when it began to pay attention to its vast potential. The masterplan for realizing an environmentally friendly hydrogen economy announced in that year presented the country's strategies for developing a hydrogen economy by 2040.

The drivers behind the masterplan were to prepare for the peak oil era with higher oil prices in the future and strengthen international climate regulations such as the Kyoto Protocol. However, concerns about oil production peaking were unfounded and a stable oil supply for consumers continued. Moreover, subsequent plans to support the attainment of the stated goals were scarce. Owing to these reasons and changes in domestic politics and the 2008 global financial crisis, among other factors, the targets in this first hydrogen strategy were not met (Kang 2021). South Korea learned two main lessons from the failure of the 2005 hydrogen masterplan. First, to achieve such long-term national targets, all plans and support must be carried out simultaneously and continuously for decades at the government level. Second, and maybe most importantly, hydrogen should make economic sense and be price-competitive to expand its market presence without long-term government support. Therefore, the most crucial support for developing the hydrogen economy should be provided in the technical sphere to allow hydrogen solutions can be

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chosen by the market (rather than because of government pressure, which various external factors may influence).

South Korea has only recently begun to accelerate its development of the hydrogen industry seriously. The Action Plan for the Development of Hydrogen Mobility, the country's second hydrogen strategy, was announced in 2015, 10 years after the first (Ministry of the Environment 2015, Ministry of Planning and Finance 2018). Its primary aim is to support the development of hydrogen vehicles after Hyundai Motors manufactured and began to sell the first fuel cell electric vehicles (FCEVs) globally in 2013. However, the Paris Agreement and need to set Nationally Determined Contributions (NDCs) provided the real push for the government to revive its hydrogen plans.

Since 2018, South Korea has demonstrated clear intentions to develop a hydrogen economy. Its goals for introducing hydrogen have been presented in vital strategic documents such as the Roadmap for the Development of a Hydrogen Economy (2019), Third Base Energy Plan (2019), Korean New Deal (2020), Scenario for 2050 Carbon Neutrality (2021), and Hydrogen Leadership Vision (2021). The establishment of the Hydrogen Economic Committee headed by the Prime Minister and the public/private consultative body H2Korea has supported these plans, as has the significant investment in R&D, subsidies, and financial and administrative support to construct the necessary hydrogen infrastructure.

As one of the potential solutions to mitigate climate change, hydrogen is expected to play a vital role in achieving the country's primary environmental target of reaching carbon neutrality by 2050, stimulating post-pandemic economic growth, and enhancing energy security by increasing locally produced energy products. South Korea is one of the world's leading exporters of consumer electronics, heavy machinery, vehicles and cargo ships, and refined petroleum. Its manufacturing sector is characterized by high energy intensity (ranked fifteenth in the world; (U.S. Energy Information Administration n.d.) and significant greenhouse gas emissions (more than twice the EU average and a little below those of the United States; Knoema n.d., International Energy Agency 2021). Therefore, the introduction of hydrogen can also help retain the competitiveness of South Korean industrial products in the global market, which is facing increasing carbon regulation. For all these reasons, hydrogen development is supported by the country's two main political parties.

While South Korea's current domestic consumption can still be met by locally produced hydrogen, the country plans to increase hydrogen consumption to over 27 million tons by 2050 (Ministry of Foreign Affairs 2021).[1] As geological constraints make it unsuitable for large-scale carbon capture, utilization, and storage (CCUS) deployment and because it cannot produce the renewable electricity required for green hydrogen, South Korea will be increasingly pushed to source clean hydrogen internationally. In particular, since cooperation with potential producers of clean hydrogen will be essential for this endeavor, it is actively expanding its collaboration with Saudi Arabia. The scope of their collaboration has thus far been limited to Saudi Arabia being an oil exporter and South Korea serving as a contractor for construction projects. However, their cooperation is developing into a strategic partnership to enhance the energy security of both countries. Hence, South Korea is becoming a key partner for Saudi Arabia to realize its Vision 2030.

The remainder of this chapter analyzes the strategic steps and plans South Korea is taking as well as its challenges in pursuing these ambitious targets, together with the role of hydrogen in achieving its economic and environmental goals. It also explores the vast scope for cooperation in the hydrogen sector between Saudi Arabia and South Korea, which is expected to provide substantial opportunities for high-level economic collaboration and enhanced energy security in both countries.

Strategy

This section discusses South Korea's motivations to develop hydrogen and measures throughout the value chain. The main message of this section is that the driving forces of hydrogen development have shifted from preparing for the post-peak oil era and strengthening international environmental regulation to mitigating climate change and pursuing decarbonization. The critical points made here are that the plans of the South Korean government are captured in several strategic documents, which show that the country has learned from its unsuccessful efforts to develop hydrogen in the 2000s. The current government's hydrogen policy focuses on incorporating hydrogen into all the sectors of the economy and conducting technological development through five main drivers:

- Diversifying energy imports (energy security)
- Increasing domestically produced energy commodities (including partially removing some imported energy)
- Achieving the country's climate ambitions by 2050 (NDCs under the Paris Agreement and carbon neutrality pledge)
- Decarbonizing industry (especially export industries threatened by carbon regulation in importing countries)
- Stimulating the economy after the COVID-19 pandemic, developing technological competencies, and creating jobs.

Nonetheless, the country's hydrogen plans have been criticized in three main directions. First, a clear definition of 'clean hydrogen' was lacking until May 2022, which created uncertainty among investors (Kim 2021a). Second, some questions on the economic and technological readiness of the country to establish a hydrogen-based economy remain unanswered. Finally, and as a result, overly ambitious and constantly increasing hydrogen targets, not supported by simultaneous technological development, are at risk of not being achieved.

Hydrogen plans: 2018 to early 2020

As discussed in the Introduction, after the failure of the 2005 hydrogen masterplan, South Korea put its hydrogen prospects on hold for almost 10 years until the ratification of the Paris Agreement in 2016 (Yonhap News Agency 2016). This agreement gave the country's leaders the impetus to accelerate hydrogen development domestically. State officials chose hydrogen as part of the central solution to achieving its NDCs and decarbonizing the manufacturing, transportation, and household sectors. As a result, South Korea recognized hydrogen as one of its top national strategic investment sectors in 2018. Together with big data and artificial intelligence, hydrogen was chosen due to its perceived potential to lead future economic growth and help create jobs (Government of South Korea 2018). The government then started to surround the hydrogen sector with unprecedented attention and support, unveiling a series of strategies and action plans at both the national and the regional levels.

From 2018, South Korea shifted from a sectoral approach to establishing a 'hydrogen economy,' which is an economic and industrial structure that uses hydrogen as the primary source of energy supply (Official South Korea website 2020). A series of state-level plans supported this holistic focus and general legislation was incorporated into South Korea's economic strategy through the documents that followed, namely, the Third Base Energy Plan, Korean New Deal, and Scenario for 2050 Carbon Neutrality (Figure 13.1).

The incorporation of hydrogen into other sectors of the economy led to the establishment of the so-called 'three pillar goals' of the hydrogen economy (Figure 13.2): developing the national economy, enhancing energy security, and meeting national decarbonization goals.

The **Roadmap for the Development of a Hydrogen Economy**, published in January 2019, formulates goals for hydrogen deployment in the mobility and energy sector, the amount of planned hydrogen supply, and localization levels and costs to 2040, with interim targets set for 2022. It also includes the National Core Technology Development Plan for hydrogen production, which focuses on two key technologies, namely steam methane reforming and water electrolysis, and sets targets for their scale and system efficiency (Intralink 2021).

A focus on the hydrogen economy was also included in the **Third Base Energy Plan**, the third instalment of South Korea's primary energy strategy, which is published every five years. In the Third Base Energy Plan, as hydrogen is classified as an energy carrier rather than a fuel or sector, its consumption is no longer reflected in the energy mix outlook (Ministry of Trade, Industry and Energy 2019b). The hydrogen economy drew little attention in the Second Base Energy Plan published in 2014. By contrast, in the First Base Energy Plan in 2008, the hydrogen economy was regarded as a crucial way of achieving so-called 'green development.'

In February 2020, as planned in the roadmap, the **Law on the Hydrogen Economy and Safety** was adopted to standardize the requirements for the safety of

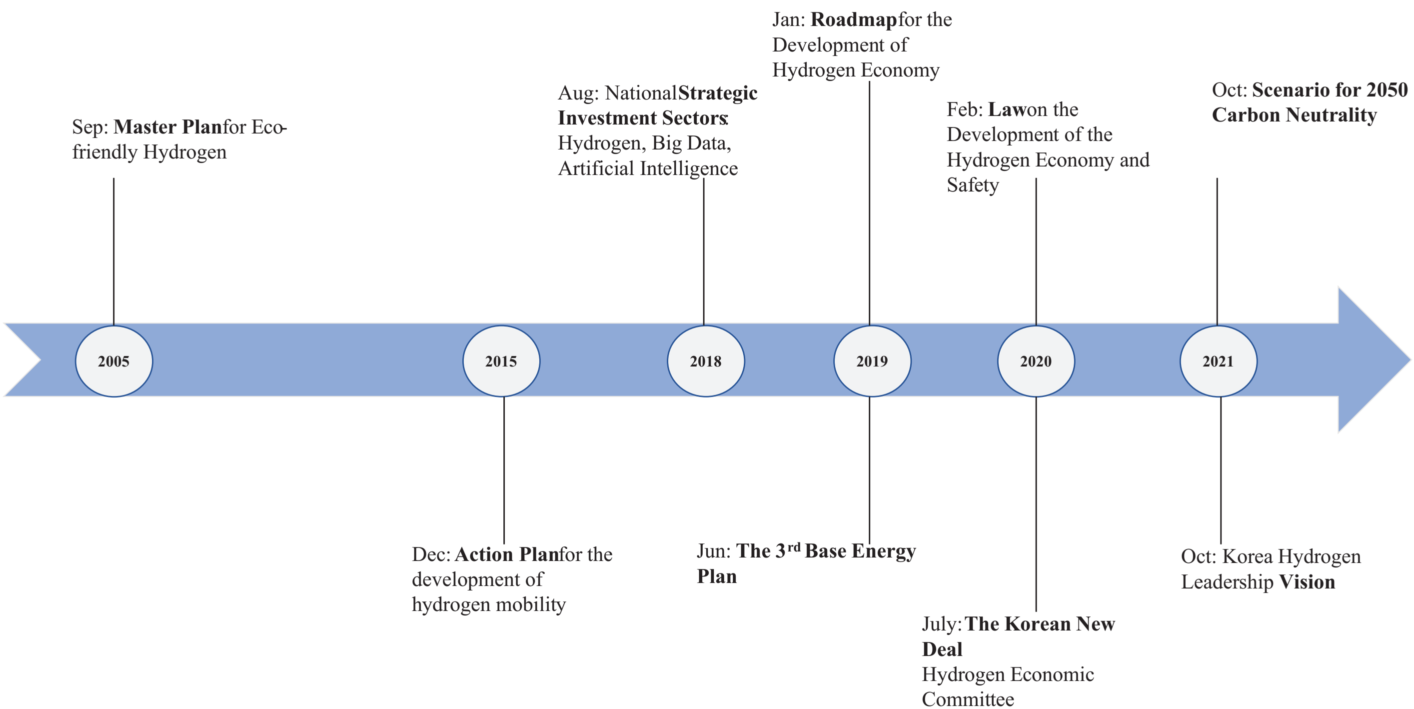

FIGURE 13.1 Timeline of hydrogen legislation in South Korea.

Source: Authors based on the Roadmap for the Development of a Hydrogen Economy and Scenario for 2050 Carbon Neutrality.

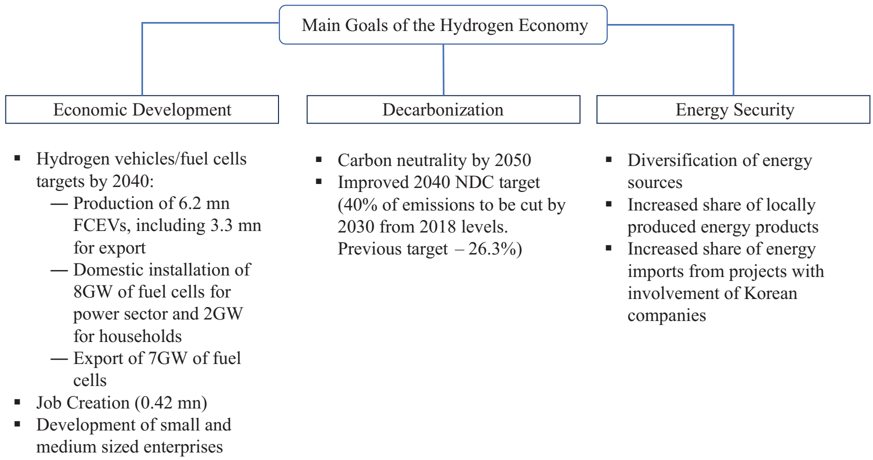

FIGURE 13.2 Primary goals of South Korea's hydrogen strategy and related targets.

Source: Authors.

hydrogen equipment, outline certification procedures, and define the responsibilities of government entities. However, defining the range of clean hydrogen became time-consuming, creating uncertainty for potential investors. Only in the revised version of the law in May 2022 did a definition of clean hydrogen appear, stating that it includes hydrogen produced from both renewable energy projects and low-carbon hydrogen projects (Park 2022).

Hydrogen plans after 2020

The COVID-19 pandemic-induced economic recession added another stimulus for hydrogen development. South Korean authorities assumed that investing in hydrogen would result in job creation in such sectors as the auto industry, which contributes over 10% of the country's GDP annually (Yoon 2021). However, stimulating the economy was not the only additional push that hydrogen in South Korea received in 2020. In 2019, after the European Commission announced the European Green Deal, which included the introduction of a Carbon Border Adjustment Mechanism, South Korea realized that this new carbon legislation might influence its trade patterns.

Companies are increasingly facing pressure from consumers and investors to meet international carbon regulations. Many of those, especially power and gas utilities, refineries, steel and automakers, and energy companies, have chosen hydrogen along with renewable energy sources to manage their risk and create a new growth engine for decarbonizing carbon-intensive businesses. South Korea sees hydrogen as a potential driver of economic growth worth 43-trillion won ($30.85 billion) and creator of 420,000 new jobs (Nakano 2021). The preference for hydrogen development is strengthened because hydrogen projects share many similarities with existing projects in which Korean companies have ample experience. As an additional measure that could result in diversifying suppliers, securing future imports of low-carbon products, and gaining new skills in hydrogen production, Korean companies are increasingly participating in hydrogen production projects overseas.

In response to the EU's New Green Deal, South Korea ushered in the **Korean New Deal**, an economic stimulation package to address the downturn caused by the COVID-19 pandemic by offering large amounts of investment and public support. As a part of this, the government plans to invest in the R&D of green hydrogen production, storage, and applications in the transport sector (Ministry of Trade, Industry and Energy 2019a). The government has also established the **Korean Hydrogen Economic Committee**, headed by the Prime Minister Chung Sye-kyun and consisting of experts from eight related ministries, including the Ministry of Trade, Industry and Energy, as well as representatives of the private sector and academia. A special 'hydrogen economy fund' of 34 billion won has been established, with which the committee plans to incept 500 hydrogen-related companies by 2030 and 1000 by 2040 (Herh 2020). Support will be provided for small and medium-sized enterprises in the following spheres: hydrogen mobility, fuel cells, liquid hydrogen, hydrogen charging stations, and water electrolysis. Support measures will include the preferential procurement of 500 companies' products by local governments and public institutions.

The government has given several organizations responsibility for developing different aspects of the hydrogen economy. For instance, the Hydrogen Fusion Alliance Promotion Group is now in charge of the hydrogen industry, while KOGAS is responsible for hydrogen distribution and the Korea Gas Safety Corp. of hydrogen safety. All these agencies are also responsible for developing professional personnel, establishing standards on hydrogen products and facilities, stabilizing hydrogen prices, and organizing a fair hydrogen distribution system (Herh 2020).

Hydrogen in industry

In the wake of the failure of the 2005 masterplan, the government is now predicting that technological progress will lower costs and make hydrogen an economically attractive solution for industry. In this vein, the **Hydrogen Leadership Vision** and **Scenario for 2050 Carbon Neutrality** were both presented in October 2021. While the Roadmap for the Development of a Hydrogen Economy sets targets and presents strategies up to 2040, the scenario includes actions and goals up to 2050 (Appendix 1). The Scenario for 2050 Carbon Neutrality consists of two options (Plans A and B) that adopt different hydrogen production technologies. However, in both plans, hydrogen plays an important role in the steelmaking industry (through the hydrogen reduction process) and transportation industry, where the penetration rate of carbon-free vehicles is expected to rise to at least 85% by 2050 (Yamanouchi 2021).

Indeed, the strategy of incentivizing industries has begun to work, resulting in increased hydrogen-related initiatives and investments by state and private companies, mainly in the energy, steelmaking, and mobility sectors, which announced multi-billion investment plans in 2021. The most significant announcement was made in April 2021, when five conglomerates (Hanwha, Hyosung, Hyundai, SK Group, and POSCO) as well as selected small and middle-sized enterprises committed to investing $38 billion to develop the entire hydrogen value chain, including R&D, production, storage, transport, and applications (Lee 2021). In addition, automakers see vast potential in hydrogen mobility applications and fuel cells, an area in which South Korean companies are early movers. For example, Hyundai Motors created the world's first commercially mass-produced hydrogen FCEVs in 2013. In addition, according to Song Ho-sung, president of KIA, a subsidiary of Hyundai Motors, the company is focusing on fuel cell military automobiles and plans to produce 500,000 civilian FCEVs as well as buses and trucks by 2030 (Park 2021; Hyundai Motors n.d.).

Role of hydrogen in achieving environmental goals

Since the announcement of the Roadmap for the Development of a Hydrogen Economy, the role of hydrogen in achieving environmental goals has been repeatedly bolstered, not taking into account the sluggish development of renewables and President Moon Jae-In's policies to gradually phase out nuclear power plants. The target hydrogen supply in the Roadmap for the Development of a Hydrogen Economy was 1.94 million tons by 2030. After the carbon neutrality pledge made in December 2020, the hydrogen supply target doubled in the Hydrogen Leadership Vision announced in October 2021. According to the Scenario for 2050 Carbon Neutrality, total hydrogen supply will increase fivefold from 2030 to 2050, from 5.26 million tons in 2030 to over 27 million tons in 2050. However, the foundation of this sharp increase is unclear.

Decarbonizing the backbone of the South Korean economy, namely, the highly energy-intensive manufacturing and energy sectors, could be extremely costly, putting hydrogen plans at risk. For instance, the decarbonization plans of two major steel manufacturers, POSCO and Hyundai Steel, might cost over $5 billion (Jung 2021). Moreover, according to some estimates, locally produced green hydrogen is unlikely to be price-competitive with domestically sourced gray and blue hydrogen even by 2040 unless it receives an electricity price discounted by almost 90% owing to the use of renewable energy sources and indirect subsidies (Kim, Kim, and Park 2020). Additional costs will be incurred to construct the required infrastructure. While a greenhouse gas emissions trading scheme that could strengthen the competitiveness of green hydrogen was established in South Korea in 2015, it remains in the early stage of development, few transactions are being made, the price is low, and the number of participants is limited (Koo 2021). At the same time, power generation using ammonia and hydrogen is also highly challenging from a technological standpoint (Kang and Jung 2021). Korean companies do not possess the technologies to produce green and blue hydrogen in large quantities and lack hydrogen storage and transportation technologies. Moreover, hydrogen-related technologies and infrastructure must develop to proceed with a series of multi-billion commercial investment plans.

Therefore, there are concerns that meeting hydrogen consumption targets might be highly challenging. The new president elected in 2022, Youn Suk-yeok, actively supports increasing the role of nuclear energy, leading experts to anticipate that the proportion of renewables in South Korea's updated strategic energy plans will reduce. At the same time, the role of LNG is expected to increase—or at least retain its current share for the foreseeable future—after LNG was included in the Korean taxonomy (Lee 2022). For these reasons, hydrogen and renewable consumption targets could be moderated or changed in future documents, while LNG and nuclear energy are highly likely to continue to play important roles in the long run.

Utilization

Supply, demand, and imports

South Korea has a well-developed natural gas infrastructure that could be used to produce hydrogen as well as an advanced petrochemical industry and refineries in which hydrogen is produced as a by-product. Hence, it is planning to rapidly increase the hydrogen supply in the short term to meet the country's consumption targets. However, while demand can be met by domestically produced gray hydrogen for the foreseeable future, South Korea has limited potential to produce the low-carbon natural gas-based and renewables-based hydrogen required to meet its greenhouse gas emission targets. Therefore, as presented in the Scenario for 2050 Carbon Neutrality, the proportion of imported low-carbon hydrogen is anticipated to grow faster after 2030.

In the Ninth Base Electricity Supply Plan announced at the end of 2020, which presents the electricity supply plan up to 2034, electricity generation capacity in 2034 is projected to be 125.1 GW, of which the capacity of renewable energy sources is expected to reach 77.8 GW. The capacity of fuel cell power generation, which is classified as a renewable energy source, is forecasted to be 2.6 GW in 2034. However, this plan does not provide a strategic target for the co-generation of ammonia with coal and hydrogen with natural gas. The plan for co-generation using ammonia and hydrogen first appeared at the Hydrogen Leadership Vision announced in 2021.

Many of the recent supply plans suggest most hydrogen will be imported in the form of ammonia by 2030 and used at coal-fired power plants to reduce CO_2 emissions during combustion (Ministry of Trade, Industry and Energy 2021d). According to the Ministry of Trade, Industry and Energy (2021a), hydrogen co-firing should achieve 50% or 150 MW by 2028, commercializing more than 30% of co-firing by 2035, and reaching 30%–100% of power generation by 2040. As for ammonia, by 2027, the demonstration of the co-firing of 20% of ammonia will be completed, while more than a half of South Korea's coal-fired thermal power plants, or at least 24 of its 43 coal-fired power plants, will commercialize using 20% of ammonia in co-firing by 2030 (Shim 2021). Korea South Power plans to co-fire ammonia at its coal-fired power station after 2024 (Ministry of Trade, Industry and Energy 2021f). The government has set a target of 13.8%–21.5% of national output from hydrogen- and ammonia-fed gas turbines by 2050 (Atchison 2021). However, no announcements about pilot projects have thus far been made.

South Korea was an early mover in adopting a hydrogen strategy. In October 2021, the country officially committed to enhance its NDCs and cut emissions by 40% from 2018 levels by 2030 (compared with the 26.3% target set as the initial goal; International Energy Agency 2020). To achieve this goal, the country must scale up clean energy technologies for electricity generation, including ammonia, significantly. Indeed, the proportion of clean energy technologies used to generate electricity is expected to rise to 4% by 2030 (Figure 13.3).

Figure 13.4 shows South Korea's hydrogen supply targets until 2050 set in the Roadmap for the Development of a Hydrogen Economy (2019), Scenario for 2050 Carbon Neutrality (2021), and Hydrogen Leadership Vision (2021). The roadmap included hydrogen supply targets for 2022, 2030, and 2040. In the Hydrogen Leadership Vision, predicted hydrogen consumption in 2030 was doubled, from 1.94 million tons to 3.9 million tons. The Scenario for 2050 Carbon Neutrality included a hydrogen consumption outlook for 2050 for the first time. According to the scenario, hydrogen consumption in 2050 is expected to be more than five times the 2040 figure shown in the roadmap, jumping from a little over 5 million tons in 2040 to over 27 million tons in 2050 in Scenarios A and B. Further. The proportion of clean hydrogen is expected to be 50% in 2030 and 100% in 2050 (Figure 13.5). However, the hydrogen supply outlook is inevitably speculative and unpredictable because no hydrogen market exists, while hydrogen is still not a commercially viable option for most sectors because of the lack of widely used and price-competitive technologies. In addition, the role of hydrogen is intentionally being expanded without a rational foundation to meet South Korea's highly challenging carbon neutrality targets.

According to the roadmap, hydrogen is expected to begin being imported before 2030 (Figure 13.5). While the specific levels of imported green, blue, and gray hydrogen in 2030 are not yet indicated, clean hydrogen imports are planned to be approximately 25% in 2030. The proportion of imported hydrogen will be above 25% because another 50% of hydrogen in South Korea will be met by gray hydrogen, including imported gray hydrogen, by that year.

The Scenario for 2050 Carbon Neutrality indicates that meeting projected demand using only domestically sourced clean hydrogen will be highly challenging. For this reason, carbon-free hydrogen should be supplied from those countries in which production costs are competitive and hydrogen can be produced in large

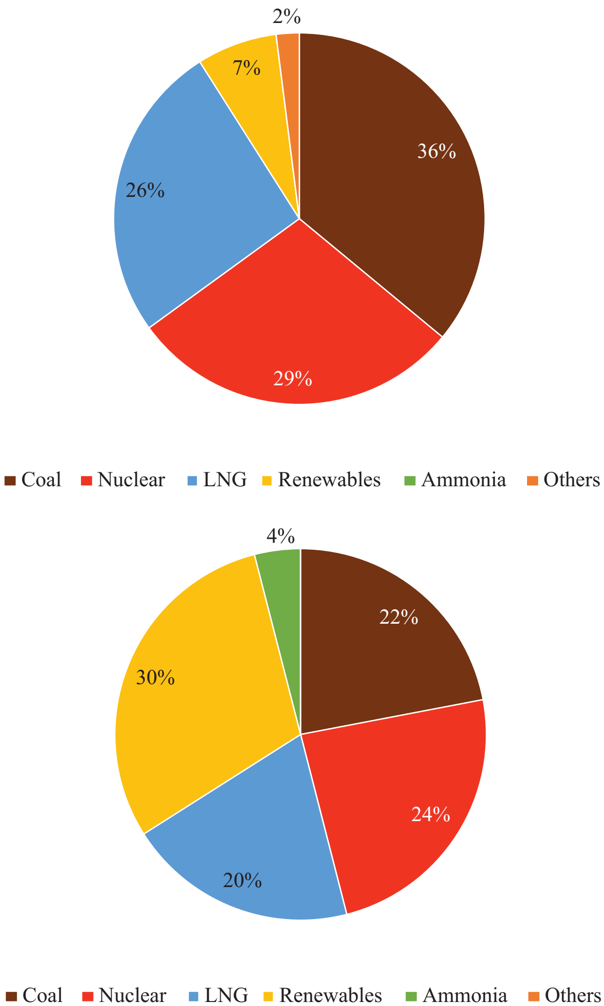

FIGURE 13.3 Technologies used for electricity generation in 2020 (left) and the NDC draft target for 2030 (right).

Source: Authors based on Kikuma (2021).

quantities. According to KEEI reports, considerable discounts on electricity from renewable energy sources will be required for domestically produced green hydrogen to be price-competitive. This explains why South Korea is seeking close cooperation with Saudi Arabia, which has the potential to produce large amounts of price-competitive clean hydrogen and ammonia. Saudi Arabia and South Korea have already shared a long history of bilateral cooperation.

In both supply outlooks for 2050, shown as Plans A and B from the Scenario for 2050 Carbon Neutrality, the proportion of internationally sourced hydrogen will

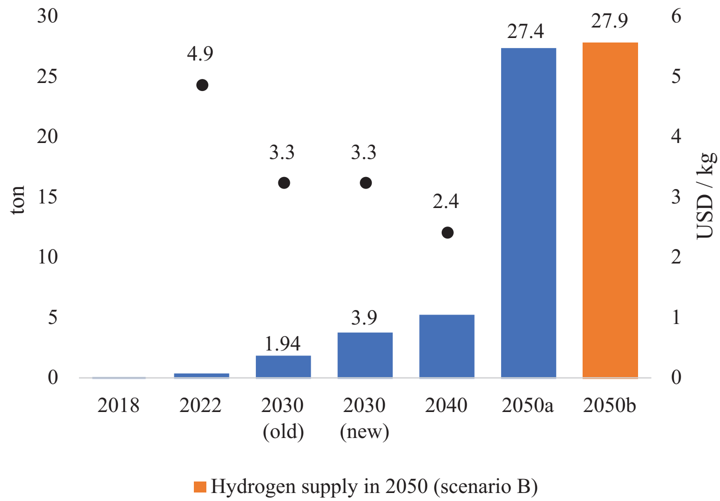

FIGURE 13.4 Hydrogen supply target/outlook and target price.

Source: Authors based on the Roadmap for Development of a Hydrogen Economy, Scenario for 2050 Carbon Neutrality, and Hydrogen Leadership Vision (updated target for 2030).

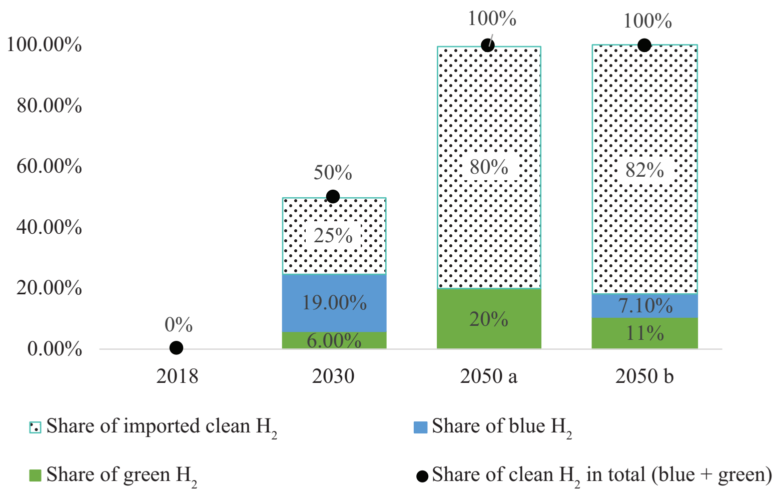

FIGURE 13.5 Planned clean hydrogen supply by type (including domestically produced hydrogen and hydrogen sourced from other countries).

Source: Authors based on the Scenario for Carbon Neutrality 2050 and Hydrogen Leadership Vision.

be around 80%. Hydrogen imports must thus increase because of South Korea's difficulties in producing large amounts of clean hydrogen, as the country intends to meet domestic demand with carbon-free hydrogen. Therefore, there is an opportunity for Saudi Arabia and other hydrogen producers to increase their market share significantly. South Korea is not only planning to import hydrogen based on purchase and sale agreements but also running joint projects to supply hydrogen to the domestic market with international partners. Therefore, it must sign partnership agreements with reliable exporters (e.g., the memorandums of understanding (MoUs) signed with Saudi Arabia in 2019 and 2022).

Transport, power, and household sectors

Hydrogen consumption is expanding its application and gradually increasing through rising hydrogen vehicle sales and fuel cell capacity. By August 2021, over 16,000 hydrogen vehicles had been sold and a fuel cell capacity of 600 MW had been installed in the power sector (Ministry of Planning and Finance 2018). To promote hydrogen, the government is adopting different measures, including public engagement. For instance, in 2019, the first police bus running on hydrogen was presented publicly in Seoul. As the former Prime Minister Lee Nak-yon stated, 'By 2028, all police buses will be those powered by hydrogen fuel cells. The new buses will not only improve working conditions for police officers but also create a better environment for Seoul residents' (Korea.net 2019). These buses are now increasingly common in Seoul metropolitan area (Figure 13.6).

Moreover, hydrogen is finding applications in even less traditional areas such as drone deliveries. In August 2021, Domino's Pizza—in collaboration with the Ministry of Land, Infrastructure, and Transport, drone company P-Square, and LG Electronics, developer of the fuel cell drone—started a pilot project in Sejong City (FuelCellsWorks 2021a). From 1 pm to 6 pm until the end of October 2021, a

FIGURE 13.6 Environmentally friendly hydrogen-fueled police bus in Seoul, June 2022.

Source: Jinsok Sung.

hydrogen drone, with the capacity to deliver two to three orders every hour, served pizza to customers every Saturday and Sunday (Sampson 2021; Figure 13.7).

The Roadmap for the Development of a Hydrogen Economy sets ambitious plans for scaling up FCEVs and the related infrastructure (Figure 13.8). It plans to build

FIGURE 13.7 Advertisement for pizzas delivered by a hydrogen-powered drone.

Source: Dilshod Akbarov.

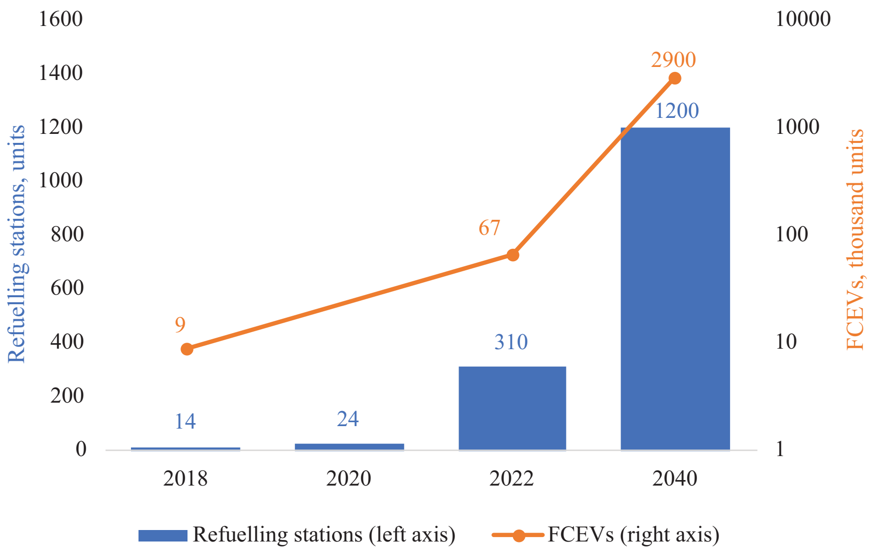

FIGURE 13.8 Number of hydrogen-refueling stations and FCEVs.

Source: Authors based on the Roadmap for the Development of a Hydrogen Economy.

1,200 refueling stations by 2040 and produce 6.2 million FCEVs, of which 3.3 million will be exported. These targets rely heavily on government subsidies, as approximately 50% of the purchase price of an FCEV and up to 50% of the installation cost of refueling stations are currently compensated (International Energy Agency 2020). As one of the action plans of Korea's New Green Deal, the expansion of environmentally friendly future mobility includes subsidies for hydrogen and electric vehicles until 2025 (Ministry of the Environment 2021). The fuel cells are produced locally by such companies as Doosan Fuel Cell, Hyundai Motors, SK Ecoplant, and S-Fuelcell.

South Korea aims to expand fuel cell usage to achieve economies of scale and, ultimately, capital costs and electricity prices. At the same time, it intends to promote the localization of critical components of fuel cells to support small and medium-sized enterprises. The target capacity of household fuel cells is expected to be over 2.1 GW in 2040 (Figure 13.9; Ministry of Trade, Industry and Energy 2019a).

Ports

South Korea will import large amounts of hydrogen via maritime shipping and plans to build hydrogen ports in Ulsan, Busan, Gunsan, Pyeongtaek, and Dangjin. Hydrogen ports are defined as ports in which hydrogen is transported, stored,

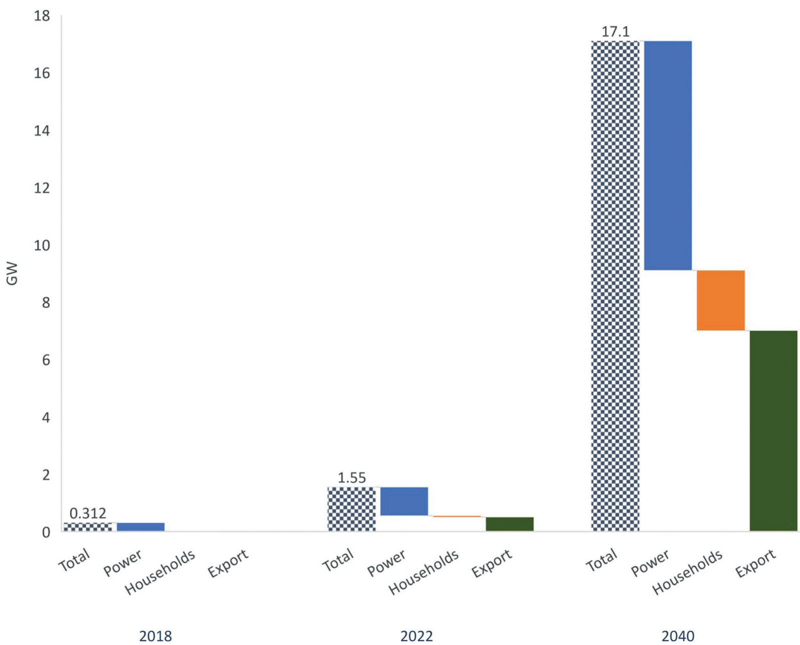

FIGURE 13.9 Planned fuel cell capacity installed in the power and household sectors and exported.

Source: Authors based on the Roadmap for the Development of a Hydrogen Economy.

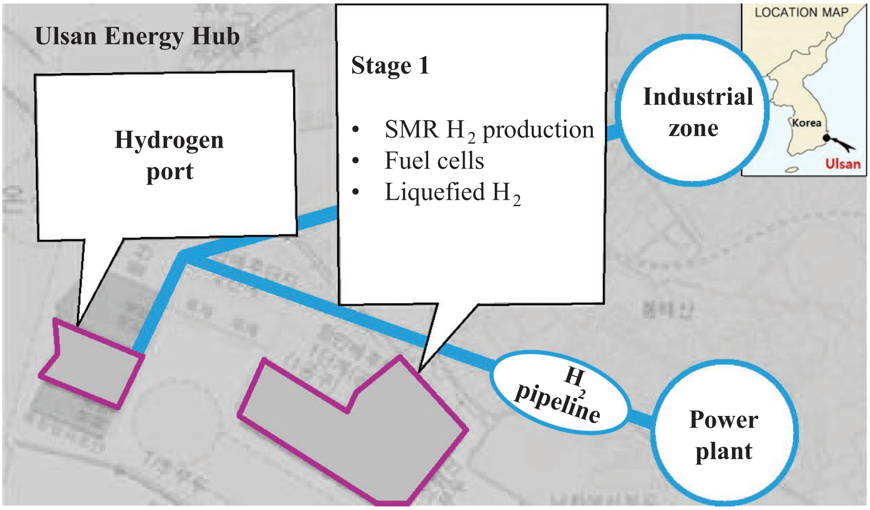

FIGURE 13.10 Planned hydrogen port at the Ulsan Oil Hub.

Source: Modified by the authors based on the Hydrogen Leadership Vision (Ministry of Trade, Industry and Energy 2021d).

applied, and produced via LNG (Figure 13.10). South Korea is also seeking to serve, supply, and transport up to 60% of domestic demand through hydrogen ports in 2040 (Ministry of Ocean and Fishery 2021).

State–private partnership and investment

Several channels of cooperation between the public and private sectors have been established to accelerate the development of the hydrogen economy. One is the public/private consultative body **H2Korea**, which has been established to improve communication between the public and private sectors. Members of H2Korea are regional governments, state-owned and private companies, including foreign enterprises, industry associations, and research institutes (H2Korea, n.d.). H2Korea also represents the South Korean hydrogen industry internationally.

Another channel is the **H2Korea Business Summit**, the Korean equivalent of the Hydrogen Council, which consists of 15 Korean companies. Its mission is to reduce the risks in the hydrogen sector by exchanging information, promoting business cooperation among member companies, and investing in companies with similar goals as well as providing policy insights into the government's plans to shift from carbon to green hydrogen by 2050 as part of its net-zero emission goal (Park and Kim 2021). The H2Korea Business Summit was created by the leaders of major South Korean companies to coordinate their efforts in establishing a hydrogen economy. The members of the Summit include some of the largest companies in the country, including five conglomerates: Hyundai

Motors, SK, POSCO, Hanwha, and Hyosung. They have announced collective investments of approximately 43-trillion won into the hydrogen economy by 2030 (Kim 2021d).

International cooperation

South Korea, as a country largely dependent on energy imports, is actively developing new hydrogen alliances to create new ties with old allies and strengthen existing cooperation, diversify sources of energy supply, and secure hydrogen supply to meet its targets. As of May 2022, South Korea had signed bilateral hydrogen agreements with Saudi Arabia, the UAE, Israel, Australia, Norway, and Chile. Agreements have also been signed at the business level. Table 13.1 and Figure 13.11 show the agreements in place at the time of writing. These agreements all lend support to the vision of the Roadmap for the Development of a Hydrogen Economy, which underlines the importance of establishing solid ties with producing countries to ensure a hydrogen supply as well as creating overseas bases through the participation of South Korean companies in overseas projects.

Further, to ensure future supplies of hydrogen from various partners and guarantee markets for its fuel cells and FCEVs, South Korea is partnering with international organizations such as the Global Green Growth Institute, which includes more than 40 developing countries. The parties have agreed to promote green hydrogen in developing countries in the MoU signed between KOGAS and the Global Green Growth Institute in September 2021. The signatories will develop joint projects and provide each other with technological assistance (The Global Green Growth Institute 2021). Since this step, the coverage of likely partners of South Korea in the hydrogen industry has increased to nearly 50 countries, making South Korea the most proactive country in forging hydrogen alliances.

Building full-scale value chains

International cooperation at the firm level includes dozens of projects. For example, Korean energy company SK E&S began a collaboration with U.S. company Monolith to become the first companies globally to produce hydrogen at a commercial level using the methane pyrolysis method. Moreover, SK E&S continues to seek cooperation with other foreign companies. For example, it recently teamed up with Australian energy giant Santos to cooperate in developing CO_2 storage facilities to produce blue hydrogen (Pekic 2022).

The company has also invested $1.4 billion in the Barosa and Caldita gas fields in Australia to import carbon-free LNG to its carbon capture and storage facility in Australia and produce blue hydrogen at its LNG regasification terminal in Boryeong (Choi 2021). This undertaking has become a part of an ambitious project to build five full-scale hydrogen value chains, ranging from production to transport,

TABLE 13.1 South Korea's cooperation (government–government and company–company) agreements globally

Country	*Content*	*Month and year*
Saudi Arabia	MoU on technological cooperation on hydrogen production, storage, transportation, hydrogen vehicles and fueling stations, and fuel cell technologies.	June 2019
	MoU between two Korean companies (steelmaker POSCO and the Samsung C&T Corporation) and Saudi Arabia's Public Investment Fund to complete project feasibility for an export-oriented green hydrogen plant (Arab News 2022a).	January 2022
	Aramco signed one agreement and nine MoUs with Korean companies on energy cooperation; among those are agreements with KEPCO, S-Oil, POSCO, Hyundai Oilbank, H2Korea, and Lotte Fine Chemical to explore potential collaborations in the supply, transportation, utilization, and certification of hydrogen and ammonia as well as the feasibility of ammonia back-cracking (Aramco 2022; see also Table 2 for more details).	January 2022
UAE	MoU between the countries on cooperating to develop a hydrogen economy and trade. In addition, GS Energy and the ADNOC signed a MoU on cooperating to develop hydrogen businesses and the energy sector (ADNOC 2021).	March 2021
	The company–company agreements concluded in 2022 are as follows: • MoU on the cooperation between Etihad Credit Insurance and the Korea Trade Insurance Corporation to support hydrogen projects financially (Nam 2022). • Business agreement between the Korea Gas Technology Development Corporation and Abu Dhabi Department of Transportation to develop green hydrogen-refueling infrastructures and technologies (Jang 2021). • Joint study agreement between ADNOC, the Korea National Oil Corporation, and SK Gas on hydrogen development. • Agreement between ADNOC and the Korea National Oil Corporation on ammonia cargo (Arab News 2022b).	January 2022
Qatar	Memorandum of collaboration on cooperation in the clean hydrogen sector (H2Korea and QatarEnergy; The Peninsula 2021).	October 2021
Oman	The Korea Gas Technology Corporation and the Omani Integrated Oil Company concluded a MoU on cooperating in hydrogen R&D as well shipping carbon-free hydrogen and ammonia from Oman (Jang 2021; Ivanova 2021).	November 2021
	POSCO will conduct feasibility studies of green hydrogen production as part of the Duqm hydrogen project (Ryu 2022).	March 2022

(*Continued*)

TABLE 13.1 (Continued)

Country	*Content*	*Month and year*
Israel	MoU on bilateral cooperation on the hydrogen economy under which South Korea will share its experience and know-how on FCEVs and fueling stations (Kim 2019).	July 2019
Australia	Letter of intent on the expansion of hydrogen cooperation to develop a hydrogen action plan and support research on hydrogen supply chains between the countries (Australian Government 2021).	September 2019
	MoU between Santos, SK E&S, the K-CCUS Association, CO2CRC, and the Korea Trade Insurance Corporation to develop CO_2 storage facilities (Pekic 2022).	February 2022
Malaysia	Agreement between Samsung Engineering, Lotte Chemical, and POSCO (in South Korea) and SEDC Energy (state-owned Sarawak Economic Development subsidiary in Malaysia) to develop a green hydrogen and ammonia project titled 'H2biscus' at Bintulu in Sarawak, Malaysia. As part of this project, hydrogen and NH_3 will be shipped to Korea (Nair 2022).	January 2022
New Zealand	Letter of intent signed by public and private sector consortia from both countries to develop technologies to ship liquid hydrogen from New Zealand to South Korea (Yi 2019).	November 2019
Norway	MoU on the hydrogen economy and low-carbon technology cooperation (technologies for the production, use, and storage of hydrogen). South Korea will provide the FCEV technologies, while Norway will provide its knowledge on the production and supply of hydrogen (Lee 2019; Shin 2019).	June 2019
Russia	The Korea Maritime Institute will participate in the 'Snowflake' project on the Yamal peninsula (TASS 2020).	November 2022
	HyPower Lap and the Hydrogen Fuel Cell Research Center under the IPCP RAS of Russia are developing mass-produced hydrogen-powered drones for delivery services (Makichuk 2021).	May 2021
Chile	MoU on exchanging technologies for producing, storing, transporting, and using clean hydrogen (Yonhap News Agency 2021).	November 2021
The United States	MoU between SK Inc. and Monolith Materials Inc. to create a joint venture to produce green hydrogen and carbon black products in South Korea. Monolith will provide the technology and training, and SK will oversee product manufacturing, sales, and distribution (SK 2021; The Korea Herald 2021).	October 2021

storage, and applications (Table 13.2). This so-called **Hydrogen Star Project** comprises five hydrogen centers in South Korea built through the cooperation of domestic and international suppliers and companies responsible for hydrogen storage, transport, and applications. The partner countries involved in this project include

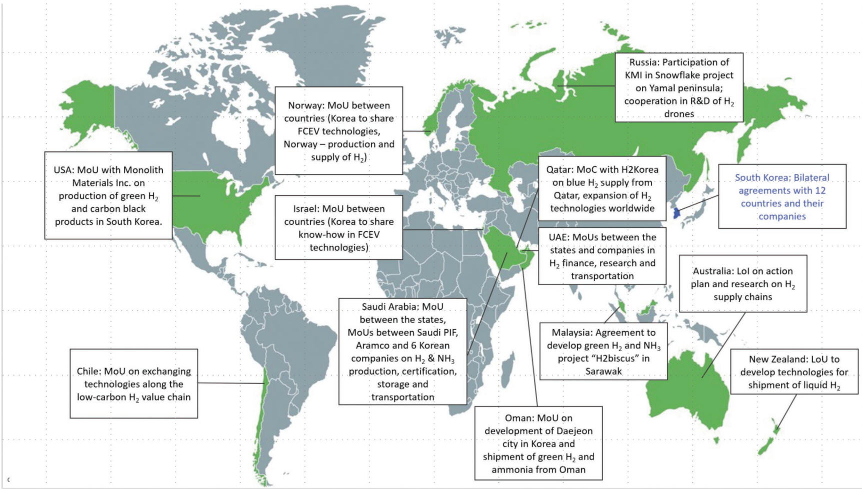

FIGURE 13.11 South Korea's global cooperation agreements for hydrogen and ammonia.

Source: Authors.

TABLE 13.2 Hydrogen Star Project: Five clean hydrogen value chain projects

Location	*Supplier(s)*	*Representative participating company*
Dangjin	Australia: blue/green ammonia, 3 million tons	Hyundai Glovis
Incheon	Saudi Arabia, Chile, and Australia	Lotte Fine Chemical
Samcheok	Oman, Australia, Malaysia, and Russia: blue/green ammonia, 4.4 million tons	POSCO
Donghae	UAE: blue ammonia, 1.14 million tons	GS Energy
Boryeong	Domestically produced blue hydrogen, 0.25 million tons (from around 2025); CO_2 to be stored abroad	SK E&S

Source: Ministry of Trade, Industry and Energy (2021d) and Kim (2021b).

major energy-exporting countries such as Australia, Chile, Saudi Arabia, Russia, the UAE, and Malaysia. However, the few scarce details on the Hydrogen Star Project available publicly only seem to summarize the various potential hydrogen import projects in South Korea. Moreover, hydrogen imports from Russia have become highly uncertain since the escalation of the Russia–Ukraine conflict.

The main idea of the Hydrogen Star Project is to import clean ammonia and hydrogen produced by electricity generated by Korean technologies and transport them to Korea by Korean tankers for the power and industrial sector. For example, Saudi Aramco and Lotte Fine Chemical have concluded a MoU on the long-term supply of blue ammonia to the Korean market. The imported ammonia will be used for power plants in the Incheon area (Table 13.2). Talks with other partners such as Chile and Australia to supply the Incheon area are ongoing (Koo 2022).

Collaboration between South Korea and Saudi Arabia/Gulf Cooperation Council (GCC) countries

The Middle East has traditionally been the primary source of South Korean LNG and oil imports (U.S. Energy Information Administration, n.d.), with Saudi Arabia being the largest supplier of crude oil to South Korea and its largest trading partner in the Gulf region. Based on the solid history of economic relations between Saudi Arabia and South Korea, the scope of economic cooperation between the two countries is being expanded into a strategic partnership. Saudi Arabia's Vision 2030 has marked South Korea as one of the Kingdom's critical partners by establishing a joint Saudi–Korean Vision 2030. In the context of Vision 2030, companies from both sides are conducting joint projects in various economic sectors, including hydrogen.

Indeed, Saudi Arabia is becoming the leading partner of South Korea in collaborating on clean hydrogen, with MoUs concluded in 2019 and 2022 and research projects already in place. Other GCC countries also view South Korea as a target market for new products, including green and blue hydrogen. The UAE recently announced its intention to capture 25% of the global low-carbon hydrogen market and considers South Korea to be one of its key export destinations along with Japan, Germany, and India (Burgess 2021). Abu Dhabi National Oil Company (ADNOC), which supplies around 10% of Korean crude oil, signed a MoU with Korean GS Energy in March 2021 to cooperate on the supply of blue ammonia. GS Energy is examining using imported ammonia for co-generation at its power plants (ADNOC 2021; Kim, Young-shin 2021).

In 2021, Oman announced the creation of a national hydrogen alliance to develop a complete hydrogen supply chain in line with the country's plans to build—until now—the largest green hydrogen plant in the world equipped with 25 GW of solar and wind power (Arab News 2021). Members of the alliance include 13 public and private sector institutions. Oman is expected to target the Asian market, especially Japan and South Korea, for potential offtake agreements.

Qatar and South Korea signed a MoU on cooperation in the hydrogen industry in October 2021 in Doha. South Korea's Hydrogen Convergence Alliance and Qatar Energy (previously Qatar Petroleum) have agreed to exchange information, promote the creation and expansion of the hydrogen market, and develop technologies as well as build a hydrogen supply chain (Graeber 2021). Considering Qatar's huge potential for developing blue hydrogen based on its sizeable natural gas reserves, South Korea has offered to help it build a blue hydrogen supply chain (Ministry of Trade, Industry and Energy 2021b).

Future cooperation might arise between South Korea and GCC countries as projects move forward. For instance, potential new shipments of green hydrogen from Saudi Arabia to South Korea might begin by 2026 once the Kingdom starts selling carbon-free hydrogen from its $5 billion project in Neom.

Research

Hydrogen cities and clusters

The South Korean government provides various subsidies through direct financing and administrative help to support R&D and executes pilot projects through government programs. The three state policies and programs aimed to support R&D and infrastructure projects at the regional level are as follows:

- **Pilot cities** have been selected to experiment with using hydrogen for their transportation and household sectors, with pilot projects using new hydrogen technologies being conducted (Park 2020).
- **Hydrogen clusters** are responsible for developing a designated hydrogen sector at an industrial scale, including transportation/storage, green hydrogen production, fuel cells, and hydrogen mobility (Korea Policy Briefing 2021).
- **Regulation-free zones**, while not specifically designed for hydrogen, are regional zones in which new technologies can be tested and developed with a lower burden of certain existing regulations (Ministry of Small and Middle-sized Enterprises and Startups 2020).

Three ministries administer these three projects. First, the Ministry of Land, Infrastructure and Transportation has chosen three cities, Ansan, Ulsan, and Jeonju-Wanju, as pilot cities. Samcheok has been selected as an R&D city and will be used as a testbed for developing hydrogen technologies and constructing a hydrogen-based town and related infrastructure. In three other pilot cities, hydrogen will be used in the transport and household sectors (Figure 13.12). In these three cities, a city-wide infrastructure based on hydrogen will be built by the end of 2022.

Second, the Ministry of Trade, Industry and Energy has listed five cities/regions as hydrogen clusters, with each responsible for developing a specific hydrogen-related sector. For example, Jeonbuk province will be creating a cluster for producing green hydrogen. In the city of Ulsan, where the factories of Hyundai Motors are located, a cluster tasked with hydrogen mobility will be constructed. These clusters must pass pre-feasibility evaluation to receive the government support to proceed with the projects.

Third, regulation-free zones are being added into designated special economic zones for the development of new industries, which have the potential to lead regional economic growth and create jobs. Amid the 4.0 Industrial Revolution, it is necessary to create an environment in which to research and test new technologies without regulatory hurdles and improve them for industrial-scale production. In these zones, companies will be exempted from specific packages of regulations to test and commercialize technologies. The Ministry of Small and Medium-Sized

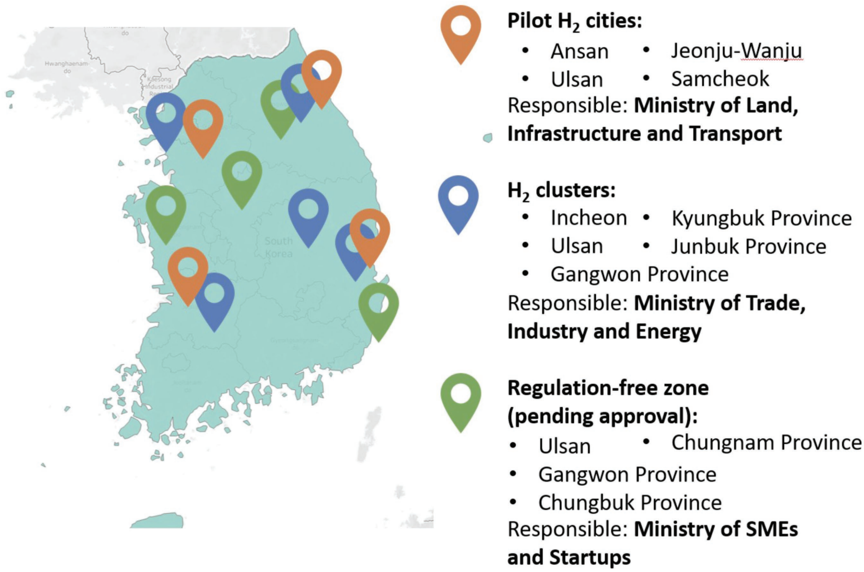

FIGURE 13.12 Pilot cities, hydrogen clusters, and regulation-free zones.

Source: Authors based on Ministry of Trade, Industry and Energy (2021c) and Ministry of Small and Medium-Sized Enterprises and Startups (2020).

Enterprises and Startups has selected several cities to advance hydrogen-related technologies. For example, Gangwon province will develop hydrogen liquefaction technologies and Chungnam province will advance fuel cells and hydrogen-refueling technologies. In Chungbuk province, green hydrogen technologies will be tested.

Ongoing research projects

South Korea is aiming to develop hydrogen technologies across the value chain from production to transportation, storage, and applications. However, many hydrogen-related technologies remain at an early stage of development and have challenges, and the country is not yet among the leaders in the production, transportation, and storage of hydrogen such as Germany and Japan.

Research is often conducted based on public–private partnerships or jointly with other companies. For example, Doosan Heavy Industries & Construction, the first Korean producer of gas turbines, is developing clean ammonia-fueled gas turbines with POSCO and the Research Institute of Industrial Science & Technology. The company is also conducting R&D on hydrogen gas turbine technology with the Korea Institute of Machinery & Materials (Lim 2021). In addition, three major

Korean ship-manufacturing companies, Samsung Heavy Industry, Daewoo Shipbuilding & Marine Engineering, and Korea Shipbuilding and Offshore Engineering, are jointly developing ammonia-powered vessels and intending to produce them commercially from 2025 (Jung 2020).

The Korea Institute of Energy Research is leading in advancing fuel cell technologies. Commercial entities such as the Hydrogen Korea Business Summit are also investing in such hydrogen technologies as production, storage, hydrogen vehicles, and fuel cells. R&D on hydrogen technologies also includes collaboration beyond the borders of the country. The Korea Institute of Energy Technology, a newly founded national university, and Fraunhofer-Gesellschaft, a leading institute in applied science in Germany, have agreed to establish a joint research center to study electrolysis in 2022. Further, as previously mentioned, hydrogen R&D is receiving support from central and regional governments and is being conducted in cooperation with state research centers as well as other Korean and international companies (Lim 2021).

Case study: hydrogen cooperation between South Korea and Saudi Arabia

Since the establishment of diplomatic relations in 1962, the economic and cultural exchanges between Saudi Arabia and South Korea have continuously developed. For the past five years, they have also been expanding into the nascent hydrogen industry. In 2017, Saudi–Korea Vision 2030 Committee was established to support Saudi Arabia's Vision 2030 through international cooperation between the two countries (Ministry of Trade, Industry and Energy 2017).

Saudi Arabia is the largest trade partner for South Korea in the Gulf region. The implementation of Saudi Arabia's Vision 2030 improved the close cooperation between Saudi Arabia and South Korea in health care, medical services, information and communications technology, and culture. This soon resulted in multiple MoUs on cooperating to develop hydrogen, signed in 2019 during the visit of Crown Prince Mohammed Bin Salman Al Saud to South Korea shortly after the announcement of the South Korean hydrogen strategy. This first MoU focused on cooperation in the automotive industry (Yonhap News Agency 2019b), and 12 agreements between Saudi Aramco and Korean companies worth $8.3 billion immediately followed (Arab News 2019). Among them was a MoU with Hyundai Motors (2019) to 'create a strategic collaboration to accelerate the expansion of the hydrogen ecosystem in the Saudi Arabian and South Korean markets.' South Korea is also seeking to become a global leader in producing and deploying FCEVs and large-scale stationary fuel cells for power generation (Nakano 2021), and Saudi Aramco and Hyundai are reported to be planning to jointly establish a hydrogen-charging infrastructure in South Korea and supply hydrogen FCEVs to Saudi Arabia (Saudi

Gazette 2019). Moreover, the companies will explore the possibility of applying advanced non-metallic materials in various industries. The concluded agreements have led to growing optimism in Saudi Arabia about the prospects of hydrogen cooperation with Asia. Aramco's leadership stated in February 2021, 'Japan and South Korea will be where the first hydrogen trading markets will begin at the end of the 2020s, early 2030s' (McQue 2021).

In March 2021, another MoU followed as Hyundai Heavy Industries Holdings Co. (HHIH) announced a new agreement with Aramco for it to deliver LPG to Hyundai Oilbank Co., a subsidiary of HHIH. The latter would convert this LPG into hydrogen for use at desulfurization facilities and for powering vehicles. The subsidiary announced plans to open up to 300 hydrogen-charging stations in South Korea by 2040 as well as 'receive blue ammonia from Saudi Aramco and use it as fuel for liquefied natural gas (LNG) boilers scheduled to be installed by 2024' to decrease emissions significantly (FuelCellsWorks 2021b).

According to a statement by HHIH, the MoU also included an agreement to transport the CO_2 emitted in the hydrogen-making process back to Saudi Arabia to be used at Aramco's oil production facilities (Ratcliffe, Kim and Park 2021). Another subsidiary of HHIH, Korea Shipbuilding & Offshore Engineering, will 'develop the world's first combined ship capable of carrying both liquefied petroleum gas (LPG) cargoes and captured carbon dioxide (CO_2)' (FuelCellsWorks 2021b). According to estimates by BloombergNEF, this is a cheaper option than transporting hydrogen. However, a clarification by Aramco rapidly followed, with the company stating that the MoU is a purely R&D opportunity with no intention to transport CO_2 (Aramco 2021).

In addition, S-Oil, the Korean subsidiary of Saudi Aramco, and Samsung C&T have agreed to jointly develop a clean hydrogen and biofuel business model, including clean hydrogen/ammonia and fuel cells. At the same time, both companies will look for possibilities to provide blue ammonia imported from Saudi Arabia to partner companies of Samsung C&T (S-Oil 2021).

Hydrogen cooperation at the state level was discussed when the Korean delegation visited Saudi Arabia in November 2021 and agreed to expand their carbon–neutral hydrogen partnership (Ministry of Trade, Industry and Energy 2021e). The experience of Korean companies in shipbuilding and plant construction and Saudi Arabia's potential to develop carbon-free hydrogen and ammonia as well as its expertise in the energy sector could lead to collaboration on advancing hydrogen/ammonia supply chains and developing related technologies.

In February 2022, South Korean President, Moon Jae-In, visited Saudi Arabia to celebrate the sixtieth anniversary of diplomatic relationships between the two countries. During Moon's visit, 14 more MoUs were signed; of them, one agreement and nine MoUs on various aspects of hydrogen cooperation were concluded between Aramco and Korean companies (Ministry of Trade,

TABLE 13.3 Agreements between Saudi Aramco and South Korean companies signed in January 2022 during the visit of the South Korean president to Saudi Arabia

Korean partner	*Contents of the agreement*
KEPCO	Intention to study the ammonia supply chain
S-Oil	Agreement to explore potential collaborations in the ammonia offtake and logistics fields
S-Oil	Agreement to explore opportunities for joint R&D on low-carbon energy solutions
POSCO	Exchange information and explore potential collaborations in the fields of blue ammonia and blue hydrogen
Hyundai Oilbank	Exchange information and explore potential collaborations in the fields of blue ammonia and blue hydrogen
H2Korea	Agreement to exchange information on hydrogen certification and regulatory requirements
S-Oil	Agreement to exchange information on Aramco's thermal crude to chemicals technology and explore potential collaborations
Export–Import Bank of Korea	Agreement of terms for strategic financing solutions
S-Oil	Agreement to collaborate on venture capital investment and start-up financing

Source: Aramco (2021).

Industry and Energy 2022). Among the signatories from the Korean side were KEPCO, S-Oil, POSCO, Hyundai Oilbank, H2Korea, and Lotte Fine Chemical. These MoUs explore potential collaborations in the supply, transportation, utilization, and certification of hydrogen and ammonia. The companies also plan to study the feasibility of converting exported ammonia into hydrogen—a process known as ammonia back-cracking. This represents the first step toward a potential large-scale production facility for hydrogen and ammonia in Saudi Arabia, which would also include a carbon capture and storage facility (Table 13.3; Aramco 2022). S-Oil will convert the blue hydrogen into ammonia and transport it to South Korea from Saudi Arabia. The imported ammonia will then be cracked into blue hydrogen or supplied without conversion to its consortium partners, including Samsung C&T and Korea Southern Power, to be used for power generation. S-Oil also plans to use hydrogen for its petrochemical facilities and other purposes such as bunker-C oil cracking and desulfurization (Kim 2021c).

In sum, the economic cooperation and hydrogen partnership between the two countries has significantly expanded over the past five years (Yonhap News Agency 2019a). As long-standing partners with a track record of cooperation across sectors, South Korea and Saudi Arabia have vast potential to collaborate to achieve the common goal of creating the hydrogen economy. The recent steps between the two countries show that their relations are now developing into a strategic partnership. Saudi Arabia is increasingly playing an essential role in providing South Korea's energy security and enhancing economic cooperation with the GCC region.

Conclusion

South Korea has begun to consider hydrogen to be a vital tool for tackling some of the most imminent challenges the country is facing, such as slowing economic growth and meeting the environmental targets set by the government, namely, Carbon Neutrality 2050 and the NDCs. To meet these ambitious goals, the proportion of renewables and supply volume of hydrogen must increase dramatically. Therefore, the government is paying great attention to developing the hydrogen market and providing full-fledged support at an unprecedented scale.

However, South Korea is geologically unfavorable for CCUS, and it is not anticipated to be able to produce sufficient electricity from renewable sources; hence, domestically sourced green hydrogen is expected to lack price competitiveness. Therefore, South Korea will face difficulties producing the large amounts of blue and green hydrogen needed to meet domestic demand and its environmental goals. If domestic hydrogen consumption grows as planned, a vast quantity of carbon-free hydrogen must be supplied to the South Korean market. While South Korea seeks to enhance energy security with domestically produced hydrogen, the hydrogen import volume is anticipated to accelerate as consumption increases yearly, up to approximately 22 million tons of around 27 million tons in 2050, according to the Scenario for 2050 Carbon Neutrality. Therefore, the country will continue to search for international cooperation to secure a stable supply. In this context, between 2019 and 2022, South Korea and Saudi Arabia signed a series of MoUs on hydrogen value chain development at both the government-to-government and the business-to-business levels.

At the beginning of developing the hydrogen market in the 2020s, South Korea plans to supply the market with domestically produced gray hydrogen, before gradually increasing the proportion of imported clean hydrogen. Therefore, South Korea may be a promising market for Saudi Arabia and countries capable of providing blue and green hydrogen and ammonia, especially after 2030. At the same time, it is developing its capabilities in hydrogen vehicles and fuel cell production and cementing its position as a leader in these sectors. For this purpose, it is also looking for markets for these products, which will likely include the Saudi market. Storage, transportation, and hydrogen production technologies still have much room for improvement. At the same time, to construct a reliable supply chain, a considerable amount of investment and time is needed. Developing a hydrogen market cannot be achieved single-handedly. As Saudi Arabia and South Korea have a long history of cooperation and partnerships in the economic sector, it is logical and beneficial for both countries to partner in the joint development of a global hydrogen market.

Note

1 The Scenario for 2050 Carbon Neutrality has two plans. According to Scenario A (B), the annual hydrogen supply in South Korea will reach 27.4 (27.9) million tons by 2050.

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APPENDIX

One Actions plans of the Scenario for Carbon Neutrality 2050 (Ministry of Foreign Affairs 2021)

Carbon Neutrality 2050 will be achieved by reducing greenhouse gas emissions in nine sectors:

1 Energy Transition (increased proportion of renewables)

- Scenario A: 70.8%
- Scenario B: 60.9%

2 Industry

Reduce greenhouse gas emissions in comparison with 2018:

- In the steel manufacturing sector, by 95%
- In the cement sector, by 53%
- In the petrochemical and refining sector, by 73%
- In other sectors, by 78.4%

3 Buildings

Reduce greenhouse gas emissions in comparison with 2018 by 88.1%

4 Transportation

- Scenario A: 97.1%
- Scenario B: 90.6%

5 Agriculture sector

Reduce greenhouse gas emissions in comparison with 2018 by 37.7%

6 Waste sector

Reduce greenhouse gas emissions in comparison with 2018 by 74%

7 Hydrogen consumption

– Scenario A: 27.4 million tons
– Scenario B: 27.9 million tons

8 Land Use, Land Use Change, and Forestry

Absorb 25.3 million tons of CO_2 in 2050

9 CCUS

Reduce CO_2 emissions in 2050 by 8.518 million tons

14

THE ROLE OF HYDROGEN IN THE RUSSIAN ENERGY SECTOR

Between the diversification of export revenues and low-carbon development

Yury Melnikov

Introduction

Hydrogen has been an integral part of Russian industry for decades. Hydrogen in Russia is primarily used for producing fertilizer and improving the quality of liquid fuels, with annual consumption reaching approximately 6.2 million tons. The Soviet space program in the 1980s called *Energia-Buran* (similar to the US Space Shuttle program) used hydrogen as a rocket fuel (Mitrova, Melnikov, and Chugunov 2019). Separate experiments on hydrogen use in air and road transport began in Russia 80 years ago, during the Second World War. However, despite the experience accumulated over all these years, scientific research, and solid industrial potential, hydrogen has not thus far been able to comprise a significant share of the Russian energy sector. However, the global energy transition and need to limit the rise in temperatures through decarbonization worldwide have created a new reality for hydrogen development in Russia. Another pressing issue is the conflict in Ukraine. This chapter therefore analyzes the strategic hydrogen opportunities in Russia in the context of global events and low-carbon developments and summarizes the ways in which all these factors could affect Russia's hydrogen strategy.

First, the author finds that the government is going to emphasize strengthening the independence of Russia's technological development. Indeed, it has already proposed boosting 23 important hydrogen-related R&D directions with five newly established dedicated national laboratories. Second, this chapter predicts a reorientation of hydrogen project initiatives away from Europe and toward the Asia-Pacific market. Finally, this chapter anticipates serious risks arising in the field of hydrogen project implementation due to complications in terms of logistical planning, payment options, and the withdrawal of technological know-how companies from the Russian market.

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The remainder of this chapter is arranged as follows. The first section provides an overview of Russia's strategic responses to these challenges and opportunities. We then analyze the possibilities for adopting hydrogen as an energy carrier in Russia as well as for exporting hydrogen. The current landscape of stakeholders involved in the R&D of hydrogen technologies is described in the third section and the Sakhalin hydrogen cluster case is reviewed in the fourth section. The final section concludes.

Role of hydrogen in the Russian Energy Strategy 2035: key drivers and barriers

Hydrogen in the Russian Energy Strategy 2035

The Russian Energy Strategy 2035 positions hydrogen in the broad portfolio of Russian energy exports for the first time (Government of Russian Federation 2020a). The strategy sets a target to export 0.2 million tons of hydrogen by 2024 and 2 million tons by 2035. On the one hand, this fact highlights policymakers' willingness to use hydrogen to diversify Russian energy exports. On the other hand, this volume accounts for only about 0.7% of the total energy equivalent of natural gas, coal, crude oil, and oil products planned to be exported from Russia under the same strategy. In addition, the energy strategy does not specify the production pathways of hydrogen or define its carbon footprint, perhaps because no reliable estimates of the potential of hydrogen production were available in 2020.

The development of hydrogen as an energy carrier in Russia is described by several published government documents (Table 14.1).

TABLE 14.1 Key hydrogen energy policy documents in Russia

Document	*Month released*	*Objective*	*Reference to hydrogen*
Russian Energy Strategy 2035	June 2020	Sets the Russian energy strategy to 2035	Sets a hydrogen export target of 0.2 million tons per annum by 2024 and 2 million tons per annum by 2035
Concept of Hydrogen Energy Development in Russia	August 2021	Identifies the areas in which hydrogen can fit into the Russian energy system by 2050	Describes the main stages of hydrogen development in the Russian energy sector
Roadmap "Development of Hydrogen Energy by 2030"	Adopted in the end of 2022, but not published	Presents the hydrogen strategy for Russia by 2030	Provides scenarios of future hydrogen production, exports and domestic demand, necessary investment, and benefits (e.g., emission reduction, tax revenues, and new jobs)

The inter-ministerial hydrogen working group under the leadership of Deputy Prime Minister Novak was created in July 2021 (Government of Russian Federation 2021a). This group includes 26 representatives from the government and the private sector.

The Concept of Hydrogen Energy Development in Russia (Government of Russian Federation 2021b) discusses the strategic focus areas, goals, and stages of development of hydrogen in the Russian energy sector by 2050. It proposes a wide range of possible hydrogen export scenarios, including up to 0.2 million tons of hydrogen exports by 2024, 2–12 million tons by 2035, and 15–50 million tons by 2050. It also describes the three main stages of hydrogen development in the Russian energy sector:

- 2021–2024: Develop supporting measures for implementing pilot projects[1]
- 2025–2035: Begin commercial projects and increase hydrogen exports and domestic applications
- 2035–2050: Develop the global market

These three documents do not explain precisely how Russia plans to achieve its goals related to hydrogen exports and technology development. Instead, they provide a general framework for discussion. The details of the targets and incentives are expected to be provided in a future document. By the end of December 2022, Russia had approved a roadmap titled "Development of Hydrogen Energy by 2030." However, as of June 2023, the roadmap had not been published. Unofficial information suggests that the strategy sets a target of producing 0.55 Mtpa of low-carbon hydrogen by 2030, with a minimal volume of exports. This represents a significant departure from the earlier drafts of the strategy in 2021–2022.

Strategic drivers of and barriers to hydrogen economic development in Russia

A number of drivers are important for policymakers to develop both a long-term energy sector and a whole economy strategy. The main drivers of low-carbon hydrogen development are to

- Decarbonize the economy
- Develop long-term renewable energy storage systems
- Improve air quality
- Diversify energy sources for energy security
- Develop the economy by exporting hydrogen and related technologies

The impact of all these drivers can be seen in Germany's hydrogen strategy (Deutsche Energie-Agentur and SKOLKOVO School of Management 2022). The highly ambitious German decarbonization policy is coupled with the need for energy storage solutions to balance intermittent renewable power generation. Strict environmental standards in transport create opportunities for electric and hydrogen-based vehicles, although in different market segments of the transport sector. Germany is also developing international hydrogen partnerships with several countries to diversify its supply options and simultaneously export domestic hydrogen technology.

By contrast, these drivers work differently in Russia. The decarbonization of the national economy is not an important driver of Russia's hydrogen ambitions. The Russian National Determined Contribution within the Paris Agreement framework to reduce greenhouse gas (GHG) emissions by 30% from the 1990 level by 2030 has already been achieved (UNFCCC 2020). According to 2017 data, GHG emissions in Russia are about half the 1990 level (Mitrova et al. 2020). The Russian low-carbon development strategy adopted in October 2021 considers inertial and target scenarios with different levels of GHG emissions and natural carbon sequestration (GHG removals by LULUCF) in 2030 and 2050 (Government of Russian Federation 2021c). The target scenario assumes a 60% reduction in net GHG emissions by 2050 compared with the level of 2019; however, this goal is expected to be achieved by offsetting emissions by more than doubling natural carbon sequestration rather than reducing emissions themselves (Figure 14.1). From this perspective, low-carbon hydrogen is difficult to consider as a necessary driver for the decarbonization of the Russian economy.

A nationwide carbon pricing system is not expected in the foreseeable future, with the exception of the Sakhalin region case, as discussed in the fourth section. The stakeholders of large Russian businesses fear that a carbon price would make them uncompetitive in the global market. In addition, regulators see the increase

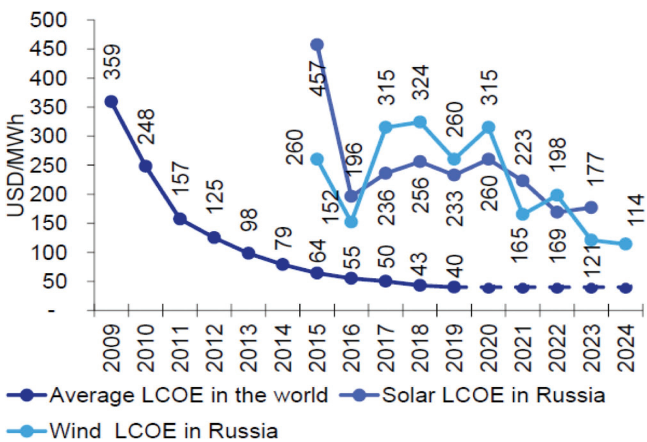

FIGURE 14.1 GHG emissions in Russia (target scenario of the low-carbon development strategy), million tons of CO_2 equivalent.

Source: Russian low-carbon development strategy adopted in October 2021.

in the energy cost for households as having unacceptable consequences. Thus, the lack of even a basic carbon (floor) price disincentivizes any effort to produce or use low-carbon hydrogen.

On the contrary, decarbonization indirectly affects a potential hydrogen outlet for Russian exporters to the European Union, including the steelmaking, petrochemicals, and pulp and paper industries. The decarbonization of these sectors is expected to become a priority once the European Union's Carbon Border Adjustment Mechanism (CBAM) comes into force. The CBAM is designed to monetize the carbon footprint of goods imported by European countries. However, whether the CBAM can create the market signals to deploy hydrogen in Russian industry remains unclear, as several other commercialized opportunities exist, including improving energy efficiency, using renewable energy, and substituting fuels.

Developing a long-term renewable energy storage system

Using hydrogen to solve the long-term energy storage issue, address the intermittency of renewable energy, and avoid renewable power curtailment is an important driver for countries actively developing renewable energy. In Russia, the rate of development of solar and wind energy is slow because of the presence of low-cost gas and coal-fired power plants as well as large hydro and nuclear plants.

Improving air quality in urban areas

This driver is especially important in countries with heavy traffic in vast cities and industrial centers, particularly when the proportion of coal used in the energy sector is high. Hydrogen fuel cell electric vehicles (FCEVs) can reduce emissions of air pollutants to zero as well as boost the development of the hydrogen infrastructure and technologies. While Russia's urban air quality problem is not as acute as that in China, for example, some niches suitable for FCEV emergence will arise as the cost of hydrogen technologies decreases. At the same time, the specificity of Russian conditions means that the problem of air pollutants from transport can also be solved by adopting natural gas vehicles (NGVs). The competitiveness of battery electric vehicles (BEVs), FCEVs, and NGVs will depend on the rate of development of the charging/fueling infrastructure.

Diversifying energy supply for energy security

In Russia, this driver is not as important as in energy-importing countries and regions. Russian regions receive affordable energy sourced from a diversified energy mix, including natural gas, coal, electricity from large hydro and nuclear power plants, and petroleum products. In remote regions in Russia's far east and Siberia, hydrogen could play a role in increasing the availability and environmental sustainability of the local power supply in the future. However, environmental regulations are required to incentivize local stakeholders to adopt sustainability measures.

Developing the economy by exporting hydrogen and hydrogen technologies

For Russia, this driver is relatively more applicable. Russian industry has been working with hydrogen for decades, and the R&D of Russian academic institutes and companies may have good potential for global commercialization (Mitrova, Melnikov, and Chugunov 2019). The export of hydrogen as a globally traded commodity could become an attractive future proposition for Russia, offering an opportunity to monetize resources and the infrastructure.

Hydrogen exports were crucial for Russian stakeholders as an alternative to natural gas and oil exports to address the increased GHG emission regulations (during 2020–2022). This was especially so in Europe, which was formerly Russia's largest natural gas export market. However, energy trade flows have changed dramatically following the Russia-Ukraine conflict. Diversifying European energy imports away from Russian energy opens an opportunity for other potential hydrogen exporters to the European Union such as Saudi Arabia to grab a significant market share in European markets. Opportunities for Russian hydrogen remain in Asia-Pacific markets, primarily Japan and Korea, especially since the requirements for carbon footprint and origin of imported hydrogen are not as strict there as in the European Union. Consequently, it will be easier for Russia to realize its potential to produce low-carbon hydrogen from natural gas.

Russian technologies are also seen as a beneficiary of global hydrogen development. Cryogenmash, a technology supplier in the liquefaction, storage, and transportation of hydrogen, was the first Russian company to join the Hydrogen Council. It has experience with liquid hydrogen since the 1960s when the Soviet space program started to use hydrogen fuel for rockets. It has been heavily integrated into international equipment supply chains for many years.

Competitiveness of Russia as a potential hydrogen exporter

Russia has the world's largest geographical potential for installing solar and wind energy, which is estimated at more than 100,000 TWh per year (Ermolenko et al. 2017). However, its large land area means that these renewable resources must be complemented with a suitable power infrastructure to connect supply with demand centers, which can be challenging. Russia is also one of the world's largest exporter of natural gas, a global leader in gas reserves, and owner of the world's largest pipeline infrastructure. In addition, Russia leads the world in exporting nuclear reactors.

The successful implementation of Russia's strategy will depend on using all these advantages in the face of the significant uncertainty about the future of the global hydrogen market in terms of growth, volumes, prices, and competition. Russia, as with many energy-rich countries, faces the possible challenge of shrinking demand for fossil fuels given most countries' pledges toward net-zero GHG emissions by the middle of this century. Indeed, the incomes of oil- and gas-producing countries from hydrocarbon sales are expected to decrease by 4.5 times in 2040–2050 compared with 2011–2020 (IEA 2021).

Policymakers must choose the best way to respond to these changes. For instance, efforts could focus on monetizing the available hydrocarbon until the middle of the century when demand is expected to decline sharply. However, this would provide other countries with an opportunity to steal share in the future hydrogen market (Poudineh and Fattouh 2020). An alternative strategy would be to diversify the export basket early by decarbonizing the production portfolio, which includes low-carbon hydrogen, to become cost-competitive using alternative energy sources. One way of being proactive would be to grow domestic hydrogen demand by pursuing more ambitious national targets to reduce GHG emissions or develop hydrogen export projects (e.g., new hydrocarbon deposits).

Hydrogen demand and supply applications

Hydrogen demand

The volume of hydrogen production in Russia is an estimated 6.2 million tons per year, with the overwhelming majority produced from natural gas without carbon capture and storage ("gray" hydrogen) and consumed at the production site (IRENA 2022). Existing consumers are mainly petrochemical and refining complexes, where hydrogen is used, for example, for producing ammonia and methanol and hydrotreating motor fuel. In the electricity sector, hydrogen is used as a coolant in electric generators at thermal and nuclear power plants, albeit comprising a low consumption volume. Based on the above analysis, the main opportunities for the potential use of hydrogen as an energy carrier are threefold: to provide power to the public transport sector, to decarbonize export-oriented industries (steelmaking and chemicals), and to supply power to remote areas.

Provide power to the public transport sector

Natural conditions in Russia are characterized by two main features, namely, a harsh climate (low air temperature in winter and high diurnal temperature variation) and long distances. Thus, hydrogen-related solutions (i.e., FCEVs) are better suited to these conditions than battery-based solutions and can become an alternative to BEVs. For example, although Moscow plans to operate more than 2,200 battery electric buses by 2024 (Moscow Transport Portal 2021), the city is ready to test hydrogen fuel cell buses once pilot tests of the refueling infrastructure have been completed (Liksutov 2021). The largest manufacturer of electric buses in Russia KAMAZ has announced its intention to pilot hydrogen buses and subsequently develop trucks and other vehicles based on FCEVs (KAMAZ 2021).

Twelve Russian cities with a total population of about 6.3 million people (Cherepovets, Lipetsk, Mednogorsk, Magnitogorsk, Chelyabinsk, Nizhny Tagil, Omsk, Novokuznetsk, Krasnoyarsk, Norilsk, Bratsk, and Chita) are participating in the Clean Air national project, which aims to reduce pollutant emissions by 20% in 2020–2024. Since transport is a significant source of pollutants in cities, BEVs and FCEVs could be a logical part of this project. In addition, the list of these cities could be expanded (Figure 14.2).

FCEV development in Russia will depend on its long-term competitiveness compared with alternatives such as BEVs and NGVs. Regulators in Russia consider the development of NGVs as an opportunity to boost the domestic natural gas market and have provided significant support since 2014. Over 2020–2024, the state could spend $263 million to support the deployment of NGVs. This will be implemented through subsidies to manufacturers of NGVs and service centers that convert gasoline and diesel vehicles to use natural gas. Additional subsidies are provided by Gazprom.

Hydrogen fuel cells can also be used in railway transport. The Russian Railway company RZD plans to abandon the purchase of diesel locomotives from 2025 in favor of electric locomotives and locomotives running on natural gas and other clean energy sources. As the company has more than 40,000 km of nonelectrified railways, hydrogen-fueled trains could occupy their niche in this segment in the future. The first such project is planned in the Sakhalin region in which RZD is working with Transmashholding, a locomotive manufacturer, to supply seven trains costing $41 million. This project is under discussion within the so-called Sakhalin hydrogen cluster, as described in the fourth section.

Decarbonize export-oriented industries

Russia's national GHG emission reduction goal is not yet supported by policy incentives for industry to decarbonize. Concurrently, the European Union's CBAM will force Russian exporters in the steelmaking, chemicals, and pulp and paper industries to decarbonize their products (Financial Times 2021). However, whether the CBAM alone can create the market signals to deploy low-carbon hydrogen in Russian industry is unclear. Galitskaya and Zhdaneev (2022) report that the minimum government subsidy should be at least 10% of capital expenditure from 2021 and gradually increase to 20% by 2040, for hydrogen production by electrolysis commercially attractive for green steelmaking. Nevertheless, several Russian exporters have already announced their interest in hydrogen as a possibly way to decarbonize their processes markedly in the long run. In 2021, NLMK, Russia's largest steelmaker, signed a memorandum of cooperation agreement with the gas company Novatek. This includes an agreement to "develop and improve hydrogen production technologies and transportation methods, as well as the use of hydrogen fuel to reduce GHG emissions" (NLMK 2021). The Russian mining and metallurgical company Metalloinvest, the world's leading producer of commercial

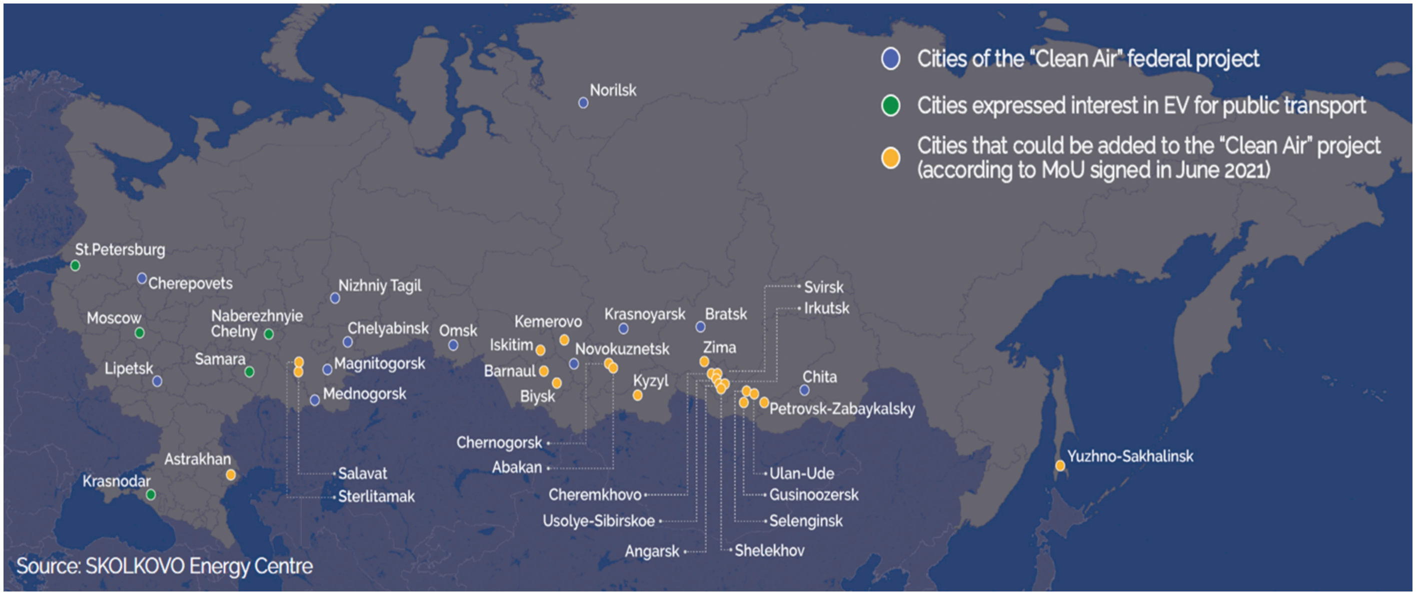

FIGURE 14.2 Russian cities that could become centers for the development of electric transport.

Source: Melnikov (2022).

hot briquetted iron, also announced its intention to construct a new plant worth \$546 million with an expected capacity of 2 million tons per year (Metalloinvest 2021). This new plant is being designed based on the principles of carbon-free metallurgy, with the prospect of a complete transition to using green hydrogen as a reducing agent. Another steelmaking company, Severstal, has invested in Ekona Power Inc., a Canadian developer of low-carbon hydrogen production technology based on methane pyrolysis (Severstal 2022). Finally, in late 2020, the gas company Novatek and Siemens signed an agreement to decarbonize liquefied natural gas production for export (Novatek 2021). As part of this agreement, the companies will consider a project to replace a proportion of the natural gas used as fuel with climate-neutral hydrogen. At the same time, the consequences of the military conflict in Ukraine make the future of such agreements extremely unclear.

As with hydrogen transport, using hydrogen to decarbonize export-oriented industries in Russia will depend on the solution's competitiveness compared with alternatives such as renewables, energy efficiency, carbon capture, usage, and storage (CCUS), and other technologies. However, the Russia-Ukraine conflict and related sanctions (e.g., ban on the import of steel products to the European Union; European Commission 2022) may impact this. The ongoing conflict could shift the focus of Russian exporters from long-term decarbonization to an urgent reorientation to alternative markets (e.g., the MENA region, China, and Turkey). However, as cross-border carbon regulation spreads outside the European Union, decarbonizing exports will remain an important task in the long term and hydrogen can play a role in that.

Supply power to remote areas

Russia's centralized unified power system provides access to electricity in the overwhelming majority of its regions. However, about 350,000 people, or around 0.2% of the population, live in remote villages and towns and receive energy mainly from local diesel-fired power plants and boilers. As diesel is delivered along complex logistical routes including rivers and winter roads, the delivery time is significant. In such settlements, the cost of electricity reaches \$460 per MWh (about 10 times more expensive than average Russian grid prices). This can rise as high as \$27,000 per MWh in some cases. Connecting such settlements to the unified power system is often impractical due to their distance from the grid. Under these conditions, remote-area power supply solutions based on renewables, energy storage, and hydrogen can be cost-effective at current technology costs and without additional support measures. For example, the electric power company RusHydro had launched projects in 47 villages in Yakutia and Kamchatka as of September 2021, including a combination of diesel power generation, renewables, and energy storage (RusHydro 2021). Although hydrogen is not under consideration due to the high costs of electrolysis, fuel cells, and other technologies, it may become a competitive option in the future as costs reduce.

Leveraging existing assets and infrastructure

Russia has the resources to produce hydrogen of any "color," but hydrogen derived from natural gas is the logical first step given its large amount of low-cost natural gas reserves and infrastructure. According to the Energy Center of the SKOLKOVO School of Management (Deutsche Energie-Agentur and SKOLKOVO School of Management 2022), the lowest estimate for blue hydrogen produced in the northern regions of Russia is just $0.90 per kg of hydrogen. There are dozens of hydrogen production project initiatives (Figure 14.3), but most are conceptual.

The most promising initiatives were Novatek's blue ammonia plant project in the Yamal region (2.2 Mta; Zabanova and Westphal 2021) and Rosatom's blue hydrogen project in the Sakhalin region (up to 0.1 Mta; Rosatom 2021b). The blue ammonia project of the Irkutsk Oil Company in eastern Siberia (IrkutskOil 2020) is another. Gazprom's activities in the hydrogen sector are also concentrated around production from natural gas (Gazprom 2021), and the company conducts R&D with several partner universities and research organizations. A key research topic is methane pyrolysis, commonly known as "turquoise" hydrogen, which makes it possible to produce hydrogen from natural gas without CO_2 emissions. Although methane pyrolysis has low technology readiness (insufficient for commercial viability), Gazprom considers this technology to be promising for large-scale hydrogen production in the future (Energy Policy 2021).

From a Russian perspective, Europe was seen as a key market; however, low-carbon hydrogen derived from fossil fuels is no longer as desired in the European Union as renewable-based hydrogen. This is due to the EU hydrogen strategy and national strategies of European countries (see Chapter 8). Therefore, the creation of green hydrogen projects is crucial. However, the prospects of Russian exports going westward are unclear because of the Russia-Ukraine conflict. The majority of promising hydrogen export projects in Russia initially focused on Asia-Pacific markets. However, the implementation of these projects could be risky given the sanctions and suspension of new business in Russia by technology partners from the European Union and the United States.

Regarding green hydrogen, the Skolkovo Energy Centre forecasted that the proportion of solar and wind in the electricity mix in Russia will reach 2%–2.5% by 2035 from less than 0.5% in 2020. Regulators are still to set targets for upgrading the proportion of renewables in the near-to-mid-term. Indeed, the slow rate of renewables deployment limits possibilities for reducing costs. As a result, the average levelized cost of electricity from new renewables in Russia is still above the international benchmark.

Reducing the cost of renewable electricity will be crucial for Russia to be able to produce green hydrogen that can compete in a future global hydrogen market. This will require scaling up by implementing a national decarbonization policy that can drive significant cost declines. Some calculations show that only extremely favorable conditions, including interest rates of no more than 4%, can lead to the

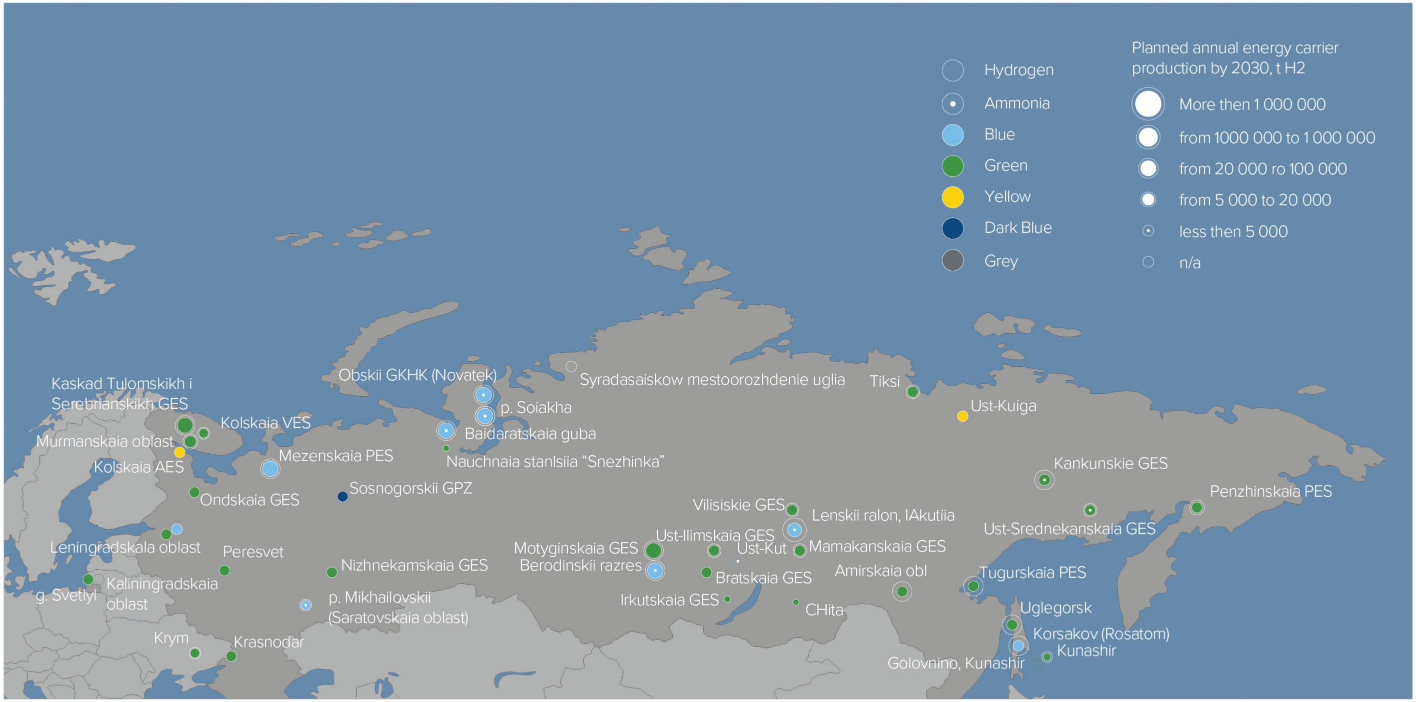

FIGURE 14.3 Hydrogen production project initiatives in Russia.

Source: Source: Melnikov (2022).

cost parity of green hydrogen fed by renewable electricity with steam methane reforming-based hydrogen in Russia. The cost parity is estimated as $1.60 per kg of hydrogen (Solyanik 2021). Nevertheless, Rusnano, Enel Russia, and Gazprom Energoholding were exploring the possibilities of producing green hydrogen in the Murmansk region (47 News 2021; Global Energy Prize Association 2021). In the same region, Rosatom has conducted a feasibility study to produce hydrogen from nuclear power (Rosatom 2021a).

Russia's regulatory authorities could strengthen the stable hydrogen demand associated with existing "gray" hydrogen production sites, oil refineries, and chemical plants. Such demand could create the necessary basis for hydrogen demand in the country, including the commercialization of relevant technologies and optimization of technical regulation. Such "hydrogen clusters" would then be able to use carbon-neutral hydrogen in the future as well as run export-oriented projects under an appropriate logistical infrastructure. For example, domestic hydrogen demand could be stimulated by a variety of measures. These include tightening transport emission standards in metropolitan areas, setting targets for hydrogen demand in the public transport industry, phasing in hydrogen content in gas distribution networks, and providing a variety of tax incentives and subsidies. All these measures would incur significant costs for both public and commercial stakeholders. Although the cost of hydrogen technologies would decrease as they scale globally, it is difficult to expect a hydrogen economy to emerge in Russia without proactive participation and regulatory support. Russian hydrogen technologies could also lose valuable opportunities for commercialization and thus global competitiveness if local hydrogen demand was limited.

Russian R&D

Hydrogen use in Russian industry is based on a solid academic foundation. In the 1980s, the Soviet Union had the world's leading scientific schools in electrochemistry and petrochemistry. Since then, however, financial constraints, limited domestic demand for technologies, and global competition with equipment suppliers, including electrolysers and methane reformers, have seriously depleted Russia's potential. In November 2020, several institutions established a hydrogen technology consortium. The aim was to coordinate the scientific community using a bottom-up approach and facilitate its communication with industry, policymakers, and other stakeholders (Scientific and Technological Consortium of Hydrogen Technologies 2022). The members of this consortium cover almost the entire spectrum of hydrogen-related research in Russia (Table 14.2).

Many of these technologies are still in their infancy.

In the hydrogen-related research landscape in Russia, several dozen research areas are under serious development; however, most technologies are not yet ready for commercialization. The development of the most promising research areas is important to reduce technology costs and stimulate the development of

TABLE 14.2 Hydrogen-related R&D in Russia

Part of hydrogen value chain	*Russian R&D*
Hydrogen production	Methane and low-temperature pyrolysis
	Various types of hydrocarbon conversion (e.g., matrix, adiabatic, oxidizing by the chemical looping principle, steam reforming in a membrane reactor)
Hydrogen purification and storage	Hydrogen storage materials with a high capacity and resistance to multiple hydrogenation-dehydrogenation cycles (including metal hydride batteries)
	Hydrogen compression
	Uninterruptible power systems based on hydrogen storage batteries
Using and transporting hydrogen	Fuel cell technologies
	Materials for fuel cells (e.g., catalysts)
	Hydrogen embrittlement of metals
	Hydrogen sensors
	Prototypes of hydrogen vehicles (e.g., unmanned cargo platforms, electric vehicles, unmanned aerial vehicles, aircraft)
	Gas turbines fired with a mix of methane and hydrogen (Power Machines 2020)

Source: Author's analysis based on data from Scientific and Technological Consortium of Hydrogen Technologies (2022).

science-intensive enterprises, which are important for the Russian economy. The Russian regulator can facilitate this process by creating a coordinating body, eliminating the duplication of tasks between stakeholders, and proposing concrete measures to support the deployment of key hydrogen technologies. There are some basic measures that can help boost hydrogen-related research. These include boosting international scientific cooperation and providing incentives and subsidies for internships of Russian scientists at leading world centers, abolishing import duties on research equipment, financing R&D on a competitive basis, and exploiting the principles of public/private partnerships.

Moreover, the Russia-Ukraine conflict and related sanctions could force regulators to focus on the development of hydrogen technologies to achieve technological independence from foreign partners. In early 2022, the Ministry of Energy proposed 23 critical R&D directions driven by five newly established dedicated national laboratories. The development of critical technologies is necessary not only to achieve technological independence but also to avoid restricting access to the necessary technologies (Federation Council 2022).

Potential for Russia and Saudi Arabia to cooperate further

Russia and Saudi Arabia, the world's largest energy exporters, have a long history of cooperation in the energy sector. The most successful recent case is OPEC+;

however, the promising areas discussed by the two governments include liquefied natural gas, petrochemicals, oil and gas extraction technologies, and nuclear energy. In an era of energy transition, both countries face the challenge of shrinking demand for their base exports and tightening international regulation. Thus, they will have to diversify their fossil fuel-based economies. In addition, the importance of cooperation in decarbonization areas such as renewables, CCUS, and new low-carbon energy carriers (i.e., hydrogen and ammonia) is growing in this new environment. Saudi Arabia can act as a competitor to Russia, including in hydrogen supply to the European Union and Asia-Pacific, and as a partner in many areas simultaneously. In May 2021, for instance, Russia offered to cooperate with Saudi Arabia to produce hydrogen (Reuters 2021).

Russia and Saudi Arabia have great potential to become prominent exporters of low-carbon hydrogen and ammonia in the future, and they are both aiming to become world leaders in this sphere. However, this potential has yet to be realized. In many ways, their situations are similar. For example, solar and wind electricity generation remains insignificant in both countries. Further, it will be necessary for both to quickly accelerate new renewables and the related infrastructure to foster the large-scale production of green hydrogen. Moreover, both countries have huge gas reserves that can be monetized through blue and turquoise hydrogen and ammonia. Most potential Russian hydrogen production projects involve exporting blue ammonia. Saudi Arabia has already implemented a pilot project in this area, having carried out the world's first international shipment of this energy carrier in September 2020.

The key area of cooperation here may be the CCUS necessary for producing blue hydrogen. Saudi Arabia has significant experience in using carbon capture and storage for enhanced oil recovery, while the carbon capture and storage potential in Russia has just begun to be explored. For example, in February 2022, Novatek obtained international certification to build 1.2 $btCO_2$ underground storage sites in the Yamal region near the location of the planned blue ammonia plant (Novatek 2022). The oilfield service competencies accumulated in both countries can also help them deploy CCUS technologies. Pyrolysis, being developed by Russian companies, may be of interest to their partners in Saudi Arabia.

Another important area for cooperation could be the active work in the field of standardization, including the standardization of safety standards for hydrogen technologies and international certification or guarantees of origin. Saudi Arabia and Russia must join international discussions on blue hydrogen to increase its acceptability in those countries. This would extend to discussion on using transparent approaches to report on methane emissions and the capture rates of carbon capture and storage technologies. In addition to these main areas of cooperation, they could collaborate on individual technologies and projects. This could include an exchange of experience between the Saudi NEOM and Russian Ecopolis projects (see the next section for more information about Ecopolis) and joint research in the fields of electrolysis, fuel cells, and methane pyrolysis.

Case study: the Sakhalin hydrogen cluster concept

Hydrogen production and demand in many countries is being scaled up through the establishment of hydrogen clusters. A hydrogen cluster is defined as locally integrated hydrogen ecosystems created from the bottom up to scale up supply and demand through the rapid deployment of low-carbon hydrogen value chains. There are synergies between the hydrogen producers, off-takers, and regional authorities within a hydrogen cluster, which reduces the long-term risks and helps the implementation of hydrogen projects.

The hydrogen cluster concept is being publicly discussed in Russia. For example, the Concept of Hydrogen Energy Development in Russia mentions four future hydrogen clusters:

- The northwestern cluster in the St. Petersburg region aimed at exporting hydrogen to Europe and reducing the carbon footprint of export-oriented enterprises.
- The Arctic cluster, which includes the regions of Murmansk, Yamal, and Kamchatka and the Northern Sea Route. This cluster focuses on creating low-carbon energy supply systems for the territories of the Arctic zone of Russia and exporting low-carbon hydrogen and ammonia.
- The eastern cluster aimed at exporting hydrogen to Asian markets and developing the appropriate hydrogen infrastructure.
- The southern cluster located in southern Russia near the Black Sea.

At the time of writing, the eastern cluster, or the Sakhalin hydrogen cluster, appears to be the most publicly known. The Sakhalin region is located on several islands in the Russian far east. This region is sparsely populated, with less than 0.5 million people in an area of 87,000 m^2 (in Jordan, with a comparable land area, there are over 11 million people residing). The structure of the regional economy is dominated by oil and gas, which constitutes at least 90% of gross regional product. The region is well located relative to the energy markets of the Asia-Pacific, as the distances by sea from the Sakhalin port of Korsakov to the largest ports in Japan, Korea, and China are between 1,700 and 2,000 km.

In late 2020, the Sakhalin government proposed making the region a suitable area for testing carbon regulation, including carbon pricing. The region is aiming to achieve net-zero GHG emissions by around 2025–2026, during which it will also create a GHG emissions management system to verify emissions and a carbon trading system. The initial CO_2 price being discussed ranges from $2 to $24.50 per ton of CO_2 equivalent (State Duma 2021). The entities in the region include those of at least 50,000 tons of CO_2 equivalent per year until 2023 and 20,000 tons of CO_2 equivalent per year until 2025. The legal framework for this experiment will be established by a new national law.

As of 2021, the Sakhalin hydrogen cluster included the following main initiatives and potential projects (Alen'kov 2021):

- The export of 30,000–100,000 tons per year of blue hydrogen.
- A hydrogen-powered train project involving the purchase of seven trains at a cost of $41 million. Based on the preliminary parameters of the project's feasibility study, Rosatom will invest $3.6 million in this project and Russian Railways will invest around $11.3 million. The third main project participant is Transmashholding. The cost of hydrogen is about $8.20 per kg, while hydrogen demand is about 330 tons per year. It is assumed that GHG emissions from a hydrogen train will amount to 0.8 tons of CO_2 per 100 km compared with 2.6 tons from a diesel equivalent (RBC 2021).
- Hydrogen for supplying power to remote areas. For this, a wind-diesel power plant near the Golovino settlement on the island of Kunashir with a capacity of 740 kW is being considered as a pilot. The project is in the concept stage (Alen'kov 2021).
- Using a methane/hydrogen blend to fuel municipal power plants and boilers.

In addition to these hydrogen production and utilization projects, the Sakhalin government plans to stimulate hydrogen-related R&D, education, engineering, and services. A new city, Ecopolis, is planned to be built close to the port of Korsakov. Ecopolis will have an area of 1,600 hectares, with a building stock of 1 million m^2, 25,000 inhabitants, and 15,000 jobs by 2030 (Sakhalin Ecopolis 2021). The masterplan presented in December 2021 (after an open international competition for architectural and urban development) includes carbon neutrality, decarbonization, and energy security as the main pillars of the Ecopolis sustainability strategy. High energy efficiency standards, 100% energy supply with renewables (solar, wind, and heating pumps), and green hydrogen-based solutions for energy storage are part of the city's energy concept. Hydrogen is planned to be used in energy supply, mobility, and seaport infrastructure (CompetitionOnline 2021).

The Sakhalin hydrogen cluster is still at an early stage of development. Its successful launch will depend on the geopolitical situation, sanctions, effective collaboration of state and nonstate actors as well as the provision of subsidies and tax incentives. While the introduction of carbon pricing may encourage regional stakeholders to use hydrogen, the carbon price being discussed may be too low to incentivize any significant hydrogen use. Important factors of the pilot's success are the level of political support from the regional government, presidential administration, and federal government as well as the speed at which the corresponding federal law will enter into force.

Conclusion: status of hydrogen development in the Russian energy sector and implications for Russia-Saudi cooperation

This chapter analyzed Russian hydrogen-related strategies and projects. Russia is signaling its interest in joining the global hydrogen race. The development of a hydrogen market in Russia is likely to be determined by export and technological opportunities as well as by climate and environmental considerations and domestic demand to a lesser degree. Monetizing the resource potential, primarily natural gas, and developing suitable scientific and technological potential will be crucial for regulators and major market players. For Russia to become a significant player in the nascent global hydrogen market, it would require a considerable investment in R&D. Furthermore, it would require pursuing technological development, offering proactive support measures, establishing public/private partnerships, and strengthening international cooperation.

However, as this chapter clarified, domestic hydrogen demand is highly uncertain, especially given Russia's geopolitical situation, energy policy, and required regulatory framework. Thus, building a strong hydrogen economy is likely to be difficult. Reaching its ambitious hydrogen export goals and securing its place in the global energy transition will require Russia to adopt more ambitious decarbonization policies at home. The new geopolitical conditions that emerged in Spring 2022 may also force Russian stakeholders to reorient to the Asia-Pacific market and try to achieve technological independence by boosting Russian-based hydrogen R&D.

Saudi Arabia can act as a competitor to Russia, including supplying hydrogen to EU and Asia-Pacific countries, and as a partner in many areas simultaneously. At the strategic level, the two countries will rely on exports. Russia and Saudi Arabia are endowed with abundant resources to produce low-cost, low-carbon hydrogen (both green and blue). However, both face similar risks. They must solve the chicken-and-egg problem regarding the uncertainty of future global hydrogen demand as well as finance and technological risks. To develop a hydrogen economy at home, both countries can look to build hydrogen clusters based on the NEOM project in Saudi Arabia and the Sakhalin hydrogen cluster in Russia.

Note

1 The concept mentions support measures such as so-called special investment contracts, which fix the parameters of investment projects and the tax environment for the project's lifetime, and compensation covering a proportion of the cost of producing high-tech products. All other measures are under consideration.

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PART 3

The clean hydrogen economy and Saudi Arabia

Hydrogen technologies

15

SCIENTIFIC UNDERSTANDING OF CLIMATE CHANGE AND AIR POLLUTION, AND THEIR INTERRELATIONSHIPS WITH THE PROSPECTIVE HYDROGEN ECONOMY IN SAUDI ARABIA

Saumitra Saxena and William Roberts

Introduction: coupling pollution mitigation with climate goals

The environmental degradation of life-sustaining natural ecosystems and resources due to air pollution is closely interlinked with the adverse outcomes of climate change. While climate change is predominantly a result of air pollution from human activities (anthropogenic), it worsens air pollution at the same time, thereby creating a vicious cycle (Fuglestvedt et al. 2003; Jacob and Winner 2009; Masson-Delmotte et al. 2021; Watts et al. 2019). Natural emissions, dust, and wildfires, often the result of aggravated climate warming, affect air quality immensely. However, although climate change and air pollution are extensively discussed separately, their interactions and a holistic approach to tackle them are overlooked (Allan et al. 2021; OECD 2016; Rao et al. 2017). Anthropogenic air pollution is regulated worldwide by limiting criteria pollutants, hazardous air pollutants, and air toxic substances; however, greenhouse gases (GHGs) such as CO_2 and methane are excluded from this category. This leaves little motivation or financial incentive for those industries responsible for air pollution (e.g., emissions of particulate matter (PM), ozone, NO_x, and SO_2) to reduce CO_2 emissions. Conversely, much of the discourse on reducing the carbon footprint and meeting net-zero targets does not consider air pollution aspects (Dreyfus et al. 2022; Masson-Delmotte et al. 2021; Sun et al. 2019). The imperative to address climate change and air pollution simultaneously is existential and necessary for all countries globally, irrespective of their development status or historic contribution to overall climate warming.

Atmospheric aerosols and surface ozone (tropospheric) constitute the most climate-relevant air pollutants and act as near-term climate forcers (Fu and Tian 2019). The radiative forcing (RF) of these two primary forcing agents is the

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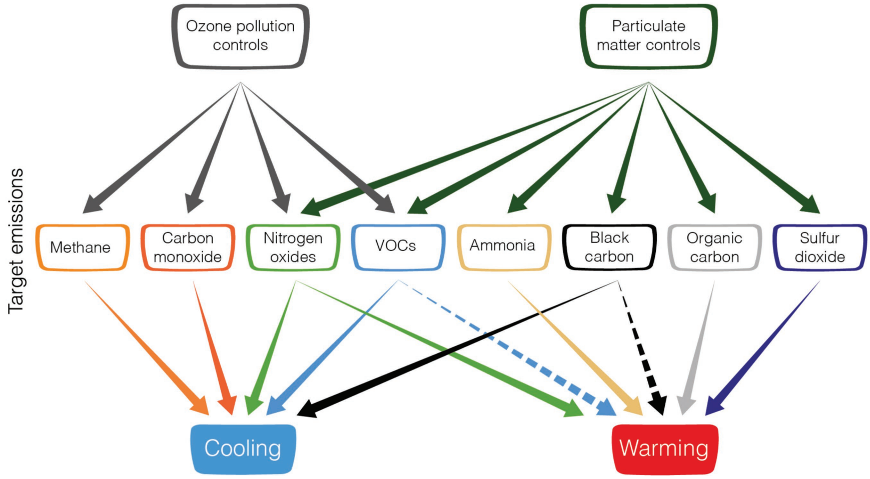

FIGURE 15.1 Impact of pollution controls on certain emissions and the overall climate. The solid black line indicates the known impact and the dashed line indicates the uncertain impact. VOC: Volatile organic compounds.

Source: Myhre et al. (2013).

cumulative effect of many interacting chemical compounds and their reaction systems in the atmosphere; these are highly modified and enhanced by emissions from natural and anthropogenic activities alike. Figure 15.1 highlights the impact of critical air pollutants (ozone and PM) on warming or cooling and their interrelationships with their respective precursors (Myhre et al. 2013). The Figure is taken from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Recent studies have focused on the impact of climate action on global warming mitigation policies (in line with the 1.5°C scenario by 2050) and considered ancillary health benefits from a reduction in air pollution. They suggest that hundreds of millions of early deaths have been avoided because of better air quality in the 21st century (Haines 2017; Jacob and Winner 2009; Markandya et al. 2018; Shindell and Smith 2019; Vandyck et al. 2020; Zhang et al. 2017). The economic gains could be substantially higher (by a factor of 1.4–2.4 depending upon the scenario) than the cost of interventions to achieve the 1.5°C target (Markandya et al. 2018). However, reducing air pollution from anthropogenic sources can worsen global warming since many air pollutants (e.g., aerosols) have a cooling effect on the atmosphere, referred to as the "climate penalty" (Masson-Delmotte et al. 2021; Hienola et al. 2018; Samset et al. 2018; Shindell and Smith 2019). Hence, air pollution-limiting policies must consider the extent to which climate warming impacts the perceived benefits and take necessary actions to accelerate climate action accordingly. Figures 15.2 and 15.3 provide the regional division of the projections of premature deaths (Figure 15.2) and health cobenefits (Figure 15.3), showing

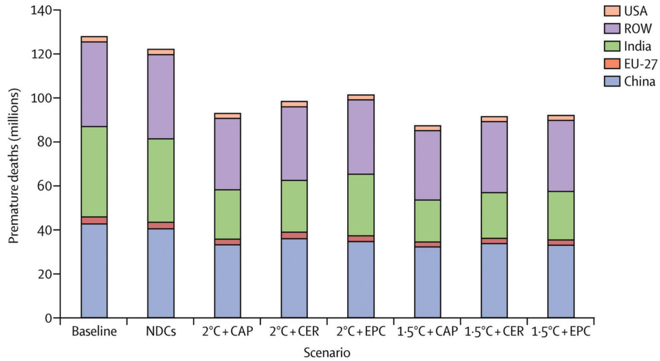

FIGURE 15.2 Cumulative premature deaths by region and scenario, 2020–2050. NDCs = Nationally determined contributions; CAP = capability scenario, where countries with high GDP per capita have low emissions allocations; CER = constant emission ratios scenario, where countries maintain their current emission ratios and preserve the status quo; EPC = equal per capita scenario, where convergence is made toward equal annual emissions per person by 2040; EU-27 = the 27 countries of the European Union in 2007; ROW = rest of the world.

Source: Markandya et al. (2018).

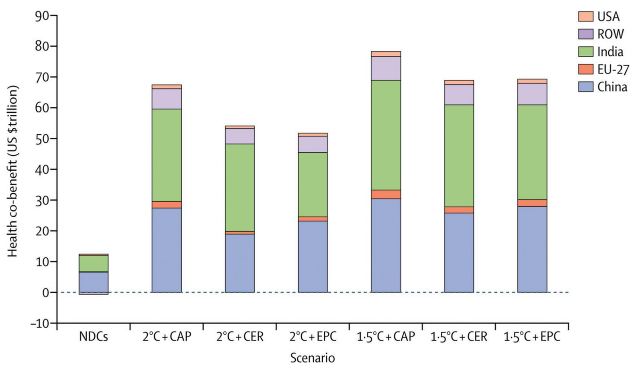

FIGURE 15.3 Cumulative health cobenefits by region and scenario, 2020–2050.

Source: Markandya et al. (2018).

how climate actions can indirectly benefit the health and financial status of a country's inhabitants.

In the following subsections, we explore air pollution and GHG emissions in Saudi Arabia. We also evaluate the benefits or limitations of the inclusion of hydrogen as a critical component of the climate solution. However, we first examine the details of significant climate matrices in the global and regional contexts as well as the sectoral division to understand better the nature of the problem and hydrogen's effectiveness as the perceived solution.

Understanding of climate science and atmospheric chemistry

The IPCC is leading the efforts to collate worldwide research and develop a global scientific understanding of climate change and the associated phenomena (Allan et al. 2021; Houghton et al. 1995). The IPCC's 2021 report, the Sixth Assessment Report (AR6), which was prepared by three working groups (WGI, WGII, and WGIII), is available in three series, titled The Physical Science Basis; Impact, Adaptation and Vulnerability; and Mitigation of Climate Change, respectively. The reports postulate that climate warming is impossible to stop without net-zero CO_2 emissions and a decrease in net non-CO_2 forcing (Allan et al. 2021).

The broad contours of the science of climate change are well known. Scientists and policymakers use the concepts of RF and global warming potential (GWP) to ensure technical understanding and recommend climate actions (Allan et al. 2021; Fu et al. 2021; Fuglestvedt et al. 2003; Houghton et al. 1995; Masson-Delmotte et al. 2021; Schimel et al. 1996; Yang et al. 2017). However, these are not perfect matrices. Hence, subjective interpretations are necessary to quantify the influences of various forcing agents and the associated benefits of their mitigation on the climate. Earth's temperature increases when gases with positive RF increase in concentration. The incoming heat is more than the outgoing proportion from the atmosphere, causing it to warm. Long-life GHG emissions (at scales of decades to centuries) are primarily responsible for much of the global warming through positive RF globally (Houghton et al. 1995; Masson-Delmotte et al. 2021).

Figure 15.4 shows how the RF concept has been employed in policymaking as well as the connection between natural and anthropogenic emissions and emitted chemical agents' atmospheric composition. Current policies, although based on the RF concept, do not directly target RF. RF only enters policy discourses indirectly via GHG emissions, short-lived air pollutants, and the associated temperature changes.

A gas's GWP is defined as the RF relative to CO_2 over a specific period. The IPCC determines GWP in 20, 100, and 500 years. A gas's GWP can thus vary widely over time; typically, policymakers use a 100-year horizon to describe the climate impact of primary GHG emissions. Some gases are more potent in the short term. We are focused, with a sense of urgency, on the 2050 deadline for the 1.5°C preferred target as envisioned in the Paris Agreement (Allan et al. 2021). Hence, forcing agents' effects on warming must be considered over a much shorter time horizon such as 10–30 years (Dreyfus et al. 2022).

Methane is a highly potent GHG gas over a 20-year horizon and is intricately linked with global warming, besides the main culprit, CO_2. Nitrous oxide and halocarbons are other important long-term GHG components. Although hydrogen is not treated as a GHG, hydrogen emissions can cause significant indirect global warming over a decadal scale (Bauer et al. 2022; Derwent et al. 2020). Scientists classify global warming agents in several ways. One of the main ways is to look at warming induced by CO_2 and non-CO_2 forcers. The role of non-CO_2 warming

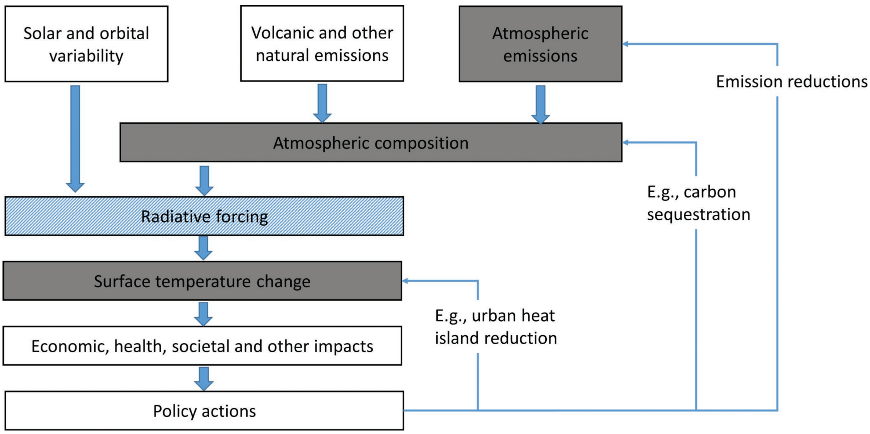

FIGURE 15.4 How RF fits into the climate policy framework. The shaded boxes indicate the quantities considered as policy targets in international negotiations and other policy analyses. RF (striped box) has not been treated as a policy target in the same explicit way as limiting emissions (e.g., Kyoto Protocol), limiting concentrations (e.g., GHG stabilization scenarios), and limiting temperature changes and impacts (e.g., environmental scenarios) have.

Source: Adapted from National Research Council and Climate Research Committee (2005).

is equally essential, although the quantification of non-CO_2 emissions and the corresponding RF is much more uncertain (Allen et al. 2022; Dreyfus et al. 2022).

Non-CO_2 sources include other GHGs (methane, nitrous oxide, halocarbons) and short-lived climate forcers (SLCFs) such as NO_x, SO_2, volatile organic compounds (VOCs), PM, and land use albedo. SLCFs, which have a scale of days or weeks, include black carbon (BC) and organic carbon (OC), aerosols, and ozone precursors, which affect RF significantly (Unger et al. 2010). Most SLCFs come from air pollution, predominantly from combustion-generated processes (Shindell and Smith 2019). Particularly, burning fossil fuels such as coal and heavy fuel oil (HFO) for power generation (Shindell and Smith 2019) and diesel, gasoline, and jet fuels for transport releases PM (in the form of BC and OC), other SLCF gases, and aerosols, producing trace metals that worsen climate change. As international marine transport uses HFO as its primary fuel of choice, it is a significant emitter of SO_2 and BC. The impact of shipping on vulnerable ecological zones such as the Arctic Circle is a tremendous source of concern (Hofmann 2022). It leads to severe climate forcing via interaction with clouds and snow cover. In this regard, the International Maritime Organization introduced sulfur caps under its 2020 regulation. However, this regulation has pushed the marine industry to use more refined fuels and indirectly shifted the burden regarding SO_2 to higher CO_2 emissions (Ji 2020).

Natural gas is a relatively clean fuel with a lower carbon footprint and air pollution impact than coal and oil. However, NO_x and hydrocarbon emissions pose significant challenges for the use of natural gas as well. The RF associated with fugitive methane emissions, the chief component of natural gas, makes it a severe climate change accelerator (Kemfert et al. 2022). Among non-anthropogenic factors, wildfires contribute to significant air pollution and are highly correlated with climate change. The other notable factors affecting RF are albedo changes due to land cover change, the deposition of BC over snow, and aerosol–cloud interactions. Land cover change can impact the climate via CO_2 emissions (positive forcing) and when the land cover area is altered (negative forcing; Arias et al. 2021).

Figure 15.5, reproduced from the IPCC's AR6 report, describes the effective RF (ERF) from CO_2 and non-CO_2 climate forcers, including SLCFs (a); the corresponding impact of Earth's temperature is estimated in (b); and (c) provides the ERF from aerosols and their interactions with clouds and radiation, calculated using different modeling methods. AR6 suggests that aerosols produce the maximum uncertainty when quantifying the cumulative RF from all sources. The underlying theme is that air pollution is intricately linked with climate change via RF (Fujimori et al. 2018; Masson-Delmotte et al. 2021; Rao et al. 2017) and must be tackled simultaneously.

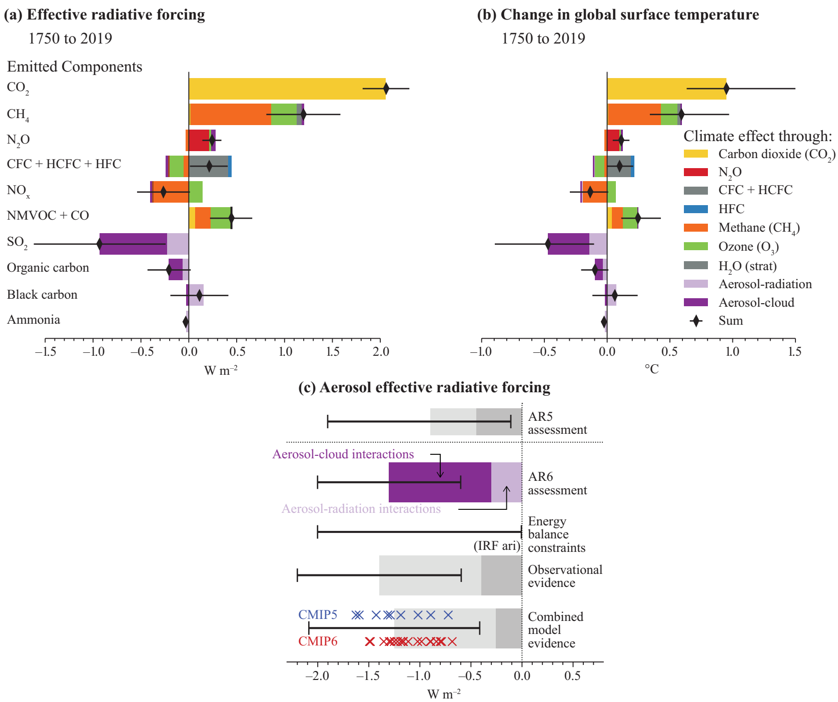

FIGURE 15.5 Figure TS.15 | Contribution to (a) effective radiative forcing (ERF) and (b) global surface temperature change from component emissions for 1750–2019 based on Coupled Model Intercomparison Project Phase 6 (CMIP6) models, and (c) net aerosol ERF for 1750–2014 from different lines of evidence. The intent of this figure is to show advances since AR5 in the

understanding of (a) emissions-based ERF, (b) global surface temperature response for short-lived climate forcers as estimated in Chapter 6, and (c) aerosol ERF from different lines of evidence as assessed in Chapter 7. In panel (a), ERFs for well-mixed greenhouse gases (WMGHGs) are from the analytical formulae. ERFs for other components are multi-model means based on Earth system model simulations that quantify the effect of individual components. The derived emissions-based ERFs are rescaled to match the concentration-based ERFs in Figure 7.6. Error bars are 5%–95% and for the ERF account for uncertainty in radiative efficiencies and multimodel error in the means. In panel (b), the global mean temperature response is calculated from the ERF time series using an impulse response function. In panel (c), the AR6 assessment is based on energy balance constraints, observational evidence from satellite retrievals, and climate model-based evidence. For each line of evidence, the assessed best-estimate contributions from ERF due to aerosol–radiation interactions (ERFari) and aerosol–cloud interactions (ERFaci) are shown with darker and paler shading, respectively. Estimates from individual CMIP Phase 5 (CMIP5) and CMIP6 models are depicted by blue and red crosses, respectively. The observational assessment for ERFari is taken from the instantaneous forcing due to aerosol–radiation interactions (IRFari). Uncertainty ranges are given in black bars for the total aerosol ERF and depict very likely ranges. {6.4.2, Figure 6.12, 7.3.3, Cross-Chapter Box 7.1, Table 7.8, Figure 7.5}.

Source: Reproduced with permission from IPCC. Chapter, figure, and section numbers referred to in this legend refer to the IPCC report (Arias et al. 2021).

Regional and sectoral attribution of RF

The Paris Agreement envisions limiting global warming to 1.5°C compared with preindustrial levels (Rogelj et al. 2018b). The signatory countries submit nationally determined contributions (NDCs) every five years. Hence, understanding the regional (or country-specific) and sectoral distribution of RF from GHGs, SLCFs, and the factors affecting albedo changes is essential to plan emission cuts and commit to those NDCs. Fu et al. (2021) quantified RF into five global regions from different sources (Figure 15.6). They also added the new categories of secondary organic aerosols, aerosol–cloud interactions, and albedo changes due to BC deposition on snow, making it a comprehensive estimation of global RF. The global anthropogenic net RF is 2.56 ± 0.58 W/m^2, including its warming (4.08 ± 0.40 W/m^2) and cooling (−1.52 ± 0.41 W/m^2) components. Essentially, 37.3±10.0% of total positive warming is masked by the cooling component globally.

CO_2 and methane are the top positive forcing contributors. Tropospheric or tertx-positive forcing effect. The negative forcing (or cooling effect) mainly comes from scattering aerosols, aerosol–cloud interactions, and albedo changes due to land cover change. Sulfates, primary organic aerosols, and nitrates produce negative forcing.

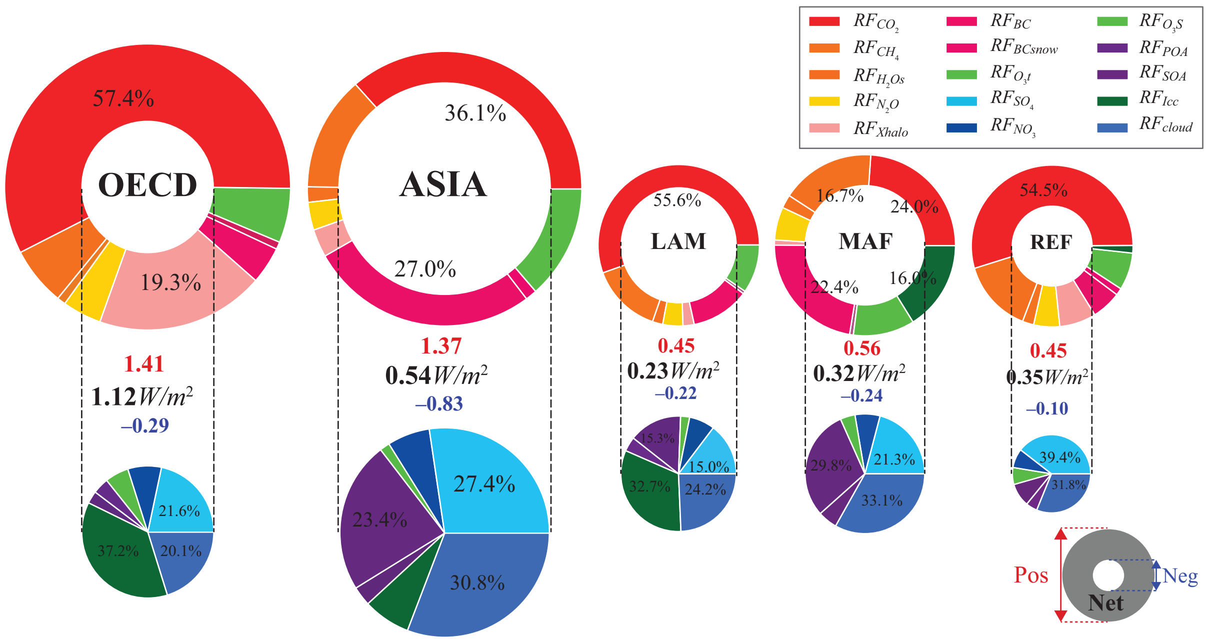

FIGURE 15.6 RF composition of five regions: OECD members (the OECD 90 and EU member states and candidates), Asian countries (ASIA; most Asian countries except for the Middle East, Japan, and former Soviet Union states), Latin America and the Caribbean (LAM), Middle East and Africa (MAF), and reforming economies (REF; the reforming economies of Eastern Europe and the former Soviet Union). For each region, the total positive RF is proportional to the area of the larger circle. The blank inner circles represent the offsets of negative RF, the composition of which is shown in the lower circle. The ring's area represents the net RF for each region.

Source: Fu et al. (2021).

The most striking observation is the extent to which regional differences, development status, and economic disparities affect the components of global RF locally. In developed countries (e.g., OECD members), CO_2, methane, nitrous oxide, BC, halogenated compounds, and tropospheric ozone are the leading global warming agents. Although highly air polluting, most aerosols influence RF negatively and thus can mask the scale of RF in certain regions (Hienola et al. 2018; Samset et al. 2018). This is undoubtedly the case with developing economies such as China, India, and countries in the Middle East and Africa. While aggregate negative forcing for OECD countries is only 20.6% of the net positive forcing, the contribution is substantially higher in other regions, including Asia (60.6%) and the Middle East and Africa (48.9%). Low-level air quality control causes the compensatory effect of negative forcing to become pronounced in these regions. As these developing countries make efforts to control air pollution, positive forcing will rise significantly, accelerating global warming (Shindell and Smith 2019). The Middle East and Africa region, although the third largest contributor to global RF, has relatively low CO_2 (24%) and a much more significant proportion of methane, BC, tropospheric ozone, and albedo due to land cover change (Figure 15.6). By contrast, negative compensatory forcing comes from emissions of primary organic aerosols, sulfates, and aerosol–cloud interactions, which are mainly from fossil fuel-based combustion-driven industries.

Some recent studies of the attribution of RF agents in broadly defined economic sectors have provided a much-needed system-level understanding of global warming from human activities (Masson-Delmotte et al. 2021; Unger et al. 2008, 2010). Economic sectors driving climate change via the cumulative RF of interacting chemical pollutants have immensely variable impacts. This approach is superior to traditional individual species RF accounting methods since it accommodates potential forcing from all activities and climate-forcing agents in a sector. Masson-Delmotte et al. (2021) estimated a sectoral division of RF for near-term and long-term scenarios. Although all the sectors listed in the IPCC study (see Figure 15.7) constitute a general classification, we can gain some insight regarding the specific GHG and SLCF emissions responsible for a sector's warming potential. Most notably, over short timescales (10–20 years), the influence of SLCFs is nearly equivalent to that of CO_2. Sectors encompassing activities in fossil fuel production and distribution, agriculture, and waste management produce the most significant warming. In the short term, methane emissions are the most critical contributor in these three sectors. Fossil fuel combustion for energy, land transportation, open biomass burning, shipping, and industrial sectors have a significant cooling contribution, which reduces net warming. The cooling comes mainly from sulfate and nitrate aerosols generated via emissions of SO_2 and NO_x, respectively. The long-term (100-year) net positive warming effect primarily comes from CO_2, as SLCFs decay over a few decades. Fossil fuel combustion, industry, and land transport generate the most CO_2 in the 2100 scenario.

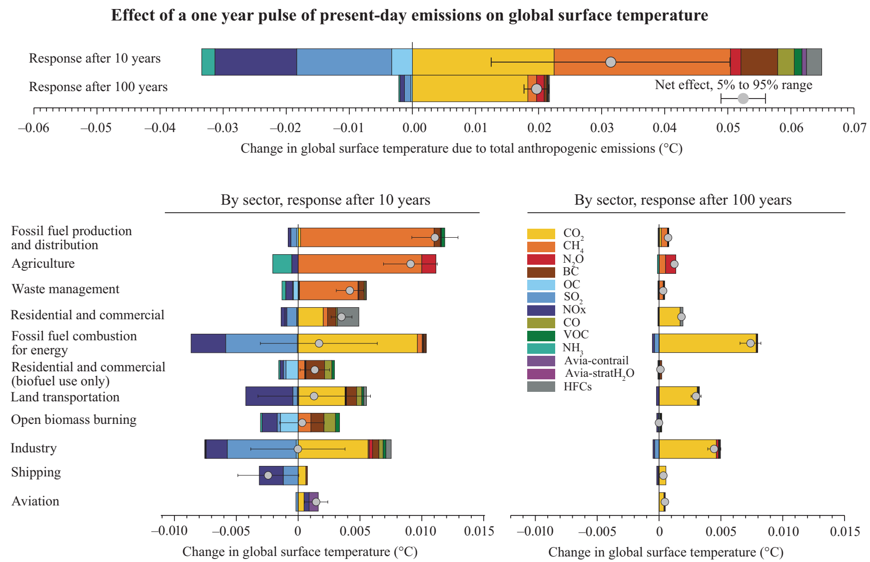

FIGURE 15.7 Figure TS.20 | Global surface temperature change 10 and 100 years after a one-year pulse of present-day emissions. The intent of this figure is to show the sectoral contribution to present-day climate change by specific climate forcers, including carbon dioxide (CO2) as well as short-lived climate forcers (SLCFs). The temperature response is broken down by individual species and shown for total anthropogenic emissions (top), and sectoral emissions on 10-year (left) and 100-year time scales (right). Sectors are sorted by (high-to-low) net temperature effect on the 10-year time scale. Error bars in the top panel show the 5%–95% range in net temperature effect due to uncertainty in radiative forcing only (calculated using a Monte Carlo approach and best estimate uncertainties from the literature). Emissions for 2014 are from the Coupled Model Intercomparison Project Phase 6 (CMIP6) emissions dataset, except for hydrofluorocarbons (HFCs) and aviation H2O, which rely on other datasets (see Section 6.6.2 for more details). CO2 emissions are excluded from open biomass burning and residential biofuel use. {6.6.2, Figure 6.16}.

Source: Reproduced with permission from IPCC. Chapter, figure, and section numbers referred to in this legend refer to the IPCC report (Arias et al. 2021).

After gaining insights into the regional and sectoral variations in emitted GHGs and SLCFs globally, we now identify the most relevant emissions for Saudi Arabia and the neighboring region and the sectors from which they originate. This information is crucial to understand how large-scale hydrogen penetration could impact these emissions and the associated RF.

Climate-impacting emissions from Saudi Arabia and the neighboring region

Geographically located in West Asia's Arabian Peninsula, Saudi Arabia is classified as part of the Middle East and North Africa (MENA) region. It occupies roughly 80% of the Arabian Peninsula and shares much of its climatic conditions with the countries in this region (Abumoghli and Goncalves 2020; Jafari et al. 2022; Waha et al. 2017; Zittis et al. 2022). Over millennia, low precipitation has given rise to arid/semi-arid areas and vast stretches of deserts in the Sahara and Arabian Peninsula. The Empty Quarter (Rub' Al Khali) and Al-Nefud deserts that fall within Saudi Arabia's boundaries are among the world's largest. This region suffers an enhanced level of warming (above average for the northern hemisphere) due to a lack of land surface energy balance adjustment via surface moisture evaporation.

This region is also home to the world's most significant oil and gas industry clusters, which have modified the regional climate via heavy emissions of GHGs and air pollution-generated climate forcers. The oil and gas industry's transitional role is at the core of most global climate discourses and is particularly important for Saudi Arabia. The highest policymaking authorities in the country are driving urgent policy actions based on the current understanding of climate science and knowledge of potential ecological scenarios (Alsarhan and Zatari 2022; AlZohbi, Alzahrany, and Kabir 2021; Belaid and Sarihi 2022). The launch of Vision 2030 has led to initiatives such as the circular carbon economy, Saudi Green Initiative, and National Renewable Energy Program as well as forays into the hydrogen economy and Zero Routine Flaring.

Recently, Saudi Arabia updated its NDC and committed to reduce 278 million tonnes of CO_2-equivalent by 2030 (Alsarhan and Zatari 2022). Total CO_2-equivalent emissions from Saudi Arabia were 720 million tonnes in 2019, roughly 1.45% of the global total of 49.8 gigatonnes (Friedlingstein et al. 2020; Hamieh et al. 2022). Within the MENA region, Saudi Arabia has the second highest emissions, standing at 18.9% of the region's total of 3.7 gigatonnes. The targeted carbon emission cut is nearly a twofold increase compared with the previous target of 130 million tonnes (Alsarhan et al. 2016). Achieving this target will require a complete understanding of the detailed quantitative contributions to GHG emissions (CO_2 and non-CO_2), SLCFs, interdependencies, and other relevant factors of individual sectors. In this context, the circular carbon economy framework does not explicitly impact SLCFs and air pollution. This understanding will enable the formulation of the necessary action plans in a timely fashion.

The Saudi Arabian economy, like those of many other countries, relies heavily on the oil and gas industry and thus must focus on mitigating air pollution as an essential component of its climate strategy. Figure 15.8 shows the division of RF components for the Middle East and Africa region, of which Saudi Arabia is one of the largest countries. Saudi Arabia's CO_2 and non-CO_2 GHGs (methane and nitrous oxide) have been extensively reported and discussed in the Fourth National Communication of Saudi Arabia submitted to the United Nations Framework Convention on Climate Change (Alsarhan and Zatari 2022). However, there is a lack of systematic measurement and reporting of most SLCFs globally, including from countries in the Arabian Peninsula such as Saudi Arabia. In this study, we focus on improving the understanding of SLCF emissions from Saudi Arabia to outline climate and air quality policies for the region.

The following section discusses atmospheric aerosols and surface ozone (terrestrial) as the most climate-relevant air pollutants and near-term climate forcers in the Saudi Arabian and regional contexts.

Atmospheric aerosols and PM

Atmospheric aerosols from natural causes (e.g., dust) and PM from air pollution sources such as the refineries, power, and transport sectors need to be addressed by Saudi Arabia for it to counter adverse climate effects (Andreae and Crutzen 1997; Charlson et al. 1987; Dayanandan et al. 2022; Houghton et al. 1995). Aerosols can also be produced from biogenic processes such as oceanic plankton (carbonyl sulfide) and non-methane hydrocarbons from vegetation (Charlson et al. 1987)[47]. Aerosols, in simple terms, are suspensions of particles (or a mix of air and particles) with a wide range of size distribution (~0.001–10 μm) and highly variable optical, physical, and chemical properties. Their measurement and classification over a geographical area are necessary to develop climate strategies. These aerosols can absorb solar radiation or scatter it back to space (direct effect) or act as nuclei for cloud droplets (indirect effect) (Houghton et al. 1995) and impact cloud formation. Aerosols affect Earth's radiative balance via direct and indirect pathways. PM can be classified as fine particles ($PM_{2.5}$ and PM_{10}) such as soot and BC or coarse particles (>10 μm) such as sulfates, nitrates, OC, and cenospheres. Primary aerosols are directly emitted into the atmosphere by sources, whereas secondary aerosols are formed by the interactions of emitted species via atmospheric chemistry. Both primary and secondary aerosols significantly impact RF in the climate, as shown in Figure 15.8.

$PM_{2.5}$ and PM_{10}

The size of the particle measured as the aerodynamic diameter is a critical determinant of its overall toxicity, health, and environmental degradation potential. For instance, $PM_{2.5}$ and PM_{10} correspond to particles with an aerodynamic diameter

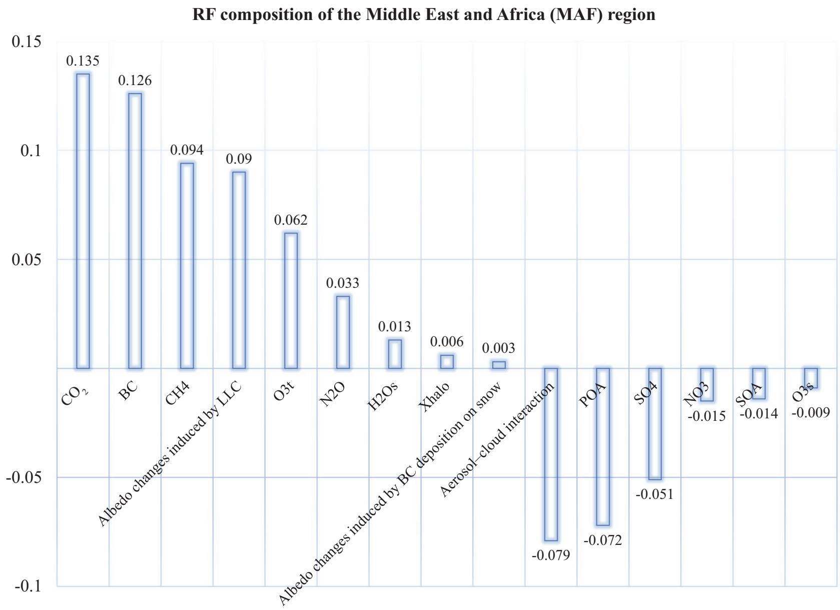

FIGURE 15.8 RF composition of the Middle East and Africa region.

Source: Based on data of Fu et al. (2021).

of less than 2.5 and 10 µm, respectively. PM belonging to the $PM_{2.5}$ category can travel deep into the respiratory tract and lead to lung and cardiovascular diseases, thereby having a more severe impact on human health. Most of these varieties of PM are direct emissions from burning and the fossil fuel supply chain. These different types of PM and their corresponding aerosols affect climate forcing in distinct ways and must be considered separately. The Gulf region suffers from high air pollution from the supply side (e.g., oil drilling sites in Saudi Arabia) and the demand side (e.g., power and transport sectors; Theys et al. 2021; Ukhov et al. 2020a, 2020b). Oil-producing countries such as Saudi Arabia are also vulnerable to massive emissions of ambient acidic gases and traces of heavy metals from refineries. Most trace metals are included in the US Environmental Protection Agency's list of toxic air pollutants and are well known for their harmful health and environmental effects. Once released, they can form primary and secondary aerosols, travel long distances, and cause water and land pollution upon deposition. Soil and water affected by toxic metals and other substances can affect the inclusion of these trace pollutants in our food chain via agriculture, farming, and fishing activities.

$PM_{2.5}$ is designated as a group-1 carcinogen by the World Health Organization (WHO) and a global threat to the environment and human health (Lim et al. 2020). Conversely, climate warming is constantly deteriorating ozone and $PM_{2.5}$ levels, resulting in climate penalties. $PM_{2.5}$ is generated from various sources, including stationary sources such as the refinery, power, desalination, and heavy industries. Road transport of trucks, buses, and cars leads to heavy vehicular $PM_{2.5}$ emissions. Saudi Arabia has exceptionally high levels of $PM_{2.5}$, far above the WHO-prescribed safe limits of 5 μg/m^3 and 15 μg/m^3 for annual and daily means, respectively. A recent study covering Jeddah, the second largest city in Saudi Arabia, identified the most prevalent sources of urban $PM_{2.5}$ emissions locally. $PM_{2.5}$ from fossil fuel and vehicular emissions comprised 45.3% and 19.1%, respectively. HFO burning was another major source of $PM_{2.5}$. Dust suspended in the atmosphere from soil, industrial sources, and sea spray accounted for 15.6%, 13.5%, and 6.5%, respectively. The overall $PM_{2.5}$ concentration was three to five times WHO's limit during the study period. High levels of trace metals from anthropogenic sources and Earth's crust were also part of the $PM_{2.5}$ composition (Nayebare et al. 2022). Other studies have examined $PM_{2.5}$'s climate-changing potential via interaction with ozone and aerosol formation for Saudi Arabia and the MENA region and reported similar outcomes (Lim et al. 2020; Meo et al. 2021).

BC and OC

Aerosols and particles that have carbon as their main element can be classified into three types, namely, BC, OC, and brown carbon, each with a distinct effect on climate forcing. While BC absorbs most of the solar radiation that falls on it, OC reflects it. BC is associated with climate warming, whereas OC produces a cooling effect. Brown carbon is organic but absorbs ultraviolet radiation, leading to warming, as with BC (Aamaas et al. 2018; Dayanandan et al. 2022; Houghton et al. 1995). BC, which is mostly in the $PM_{2.5}$ category, is also known as soot or elemental carbon (Buseck et al. 2012). It has very low reflectivity, which means it absorbs most radiation (hence "black") and leads to climate warming. BC is a positive climate enforcer with 400–1,600 times more warming potential than CO_2, although it has a very short lifetime (4–12 days). It is considered to be the second most important climate forcer after CO_2. It is typically the result of the incomplete combustion of fossil fuel/biomass and forest fires and is released with other products of combustion (Bond et al. 2012; Sharma and Mishra 2022). One of the major concerns associated with BC is the melting of glaciers, as in the Arctic and Himalayan regions. The Arctic Circle ecology and ice cover have been severely impacted by the BC emissions caused by HFO burning in the marine transport industry.

OC is a mixture of hundreds of carbon-based compounds produced from fossil fuel or biomass burning as well as natural biogenic emissions. When produced from burning fossil fuels, OC is invariably mixed with BC and sulfates. The mixture of OC is highly complex and intractable using simplistic models. However, in general, its effect is cooling via scattering. Some studies suggest that OC's negative RF contribution is the second most significant after sulfate aerosols, reinforcing its importance to climate science.

Dust

A regional feature of Saudi Arabia's climate originates from the dust aerosols produced from the arid plains and deserts of Africa, the Arabian Peninsula, and the Indian subcontinent (Jafari et al. 2022). These dust aerosols have high seasonal variation and significantly impact solar radiation, wind circulation at land and sea, cloud properties, and rainfall (Gandham et al. 2022) in complex interactions with other climate-altering agents (Klingmüller et al. 2019). Scientific estimates suggest that roughly half of the global dust emissions (1,000–2,000 million tonnes/year) originate from the MENA region, which produces the world's most extensive solar radiative cooling near the southern Red Sea (60 W/m^2; Ukhov et al. 2022a). A NASA satellite captured a striking image of airborne dust blowing out of northeast Africa into the Arabian Peninsula via the Red Sea (see Figure 15.9). Such dust storms severely affect seasonal climates by influencing RF in various ways. In cloudless conditions, they reflect sunlight and cause cooling near Earth's surface. However, the dust can absorb solar radiation in the atmosphere and produce warming effects (Gharibzadeh, Bidokhti, and Alam 2021; Gharibzadeh et al. 2019).

Several recent studies have focused on the role of atmospheric aerosols in and around Saudi Arabia (Ali et al. 2020; Dayanandan et al. 2022; Farahat 2016; Farahat, El-Askary, and Dogan 2016; Gandham et al. 2022; Gharibzadeh, Bidokhti,

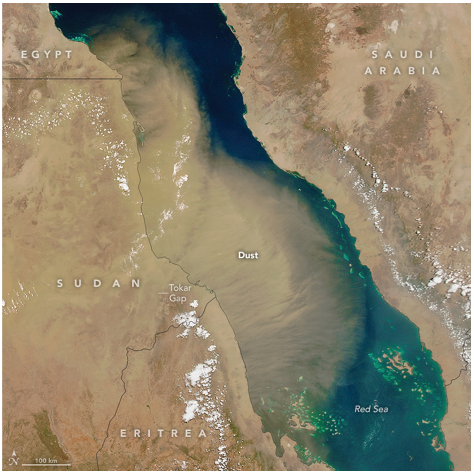

FIGURE 15.9 Dust storms over the Red Sea. The Moderate Resolution Imaging Spectroradiometer instrument on NASA's Aqua satellite captured this image of airborne dust in June 2016. The winds appear to be blowing east/northeast out of Africa.

Source: Schmaltz (2016). We acknowledge the use of data and/or imagery from NASA's Land, Atmosphere Near real-time Capability for EOS (LANCE) system (https://earthdata.nasa.gov/lance), part of NASA's Earth Observing System Data and Information System (EOSDIS).

and Alam 2021; Gharibzadeh et al. 2019; Ukhov et al. 2022a). Dust is not the only aerosol source in the MENA region. Aerosols from burning fossil fuels in industry, road transport, and power production are also observed in significant quantities. The aerosols over the skies of Saudi Arabia and the Middle East vary on a seasonal and local basis. A study analyzed the aerosols over eastern Saudi Arabia and reported that mineral dust (70%) and sulfates (20%) were dominant, with smaller proportions of OC, sea salt, and BC (Dayanandan et al. 2022; Jassim et al. 2022). Another study found that dust (local and originating from the Sahara region) and mixed aerosols (dust and BC) are the predominant sources (Ali et al. 2020). Sand and desert dust could be accelerated by climate change in areas that have petrochemical industries, high concentrations of shipping, and vehicular traffic. Although dust constitutes roughly 95% of the aerosols in Saudi Arabia, anthropogenic aerosols (or PM) are additional contributors in urban and industrial settlements. Hence, dust's interaction with air pollution generating PM aerosols is also a serious concern for this region (Klingmüller et al. 2019).

Figure 15.10 presents the modeled anthropogenic RF associated with mineral dust–pollution interactions (Klingmüller et al. 2019). Negative forcing dominates the atmosphere over large parts of the dust belt, from West Africa to East Asia. Scientists have pointed out that dust has built up in the Arabian Peninsula over the last decade, leading to long-term health and global climatic effects, including local issues regarding water management, agriculture, and marine ecology (Ravi Kumar et al. 2019). Air quality also severely deteriorates and the efficiency of renewable energy equipment reduces due to regular dust buildup.

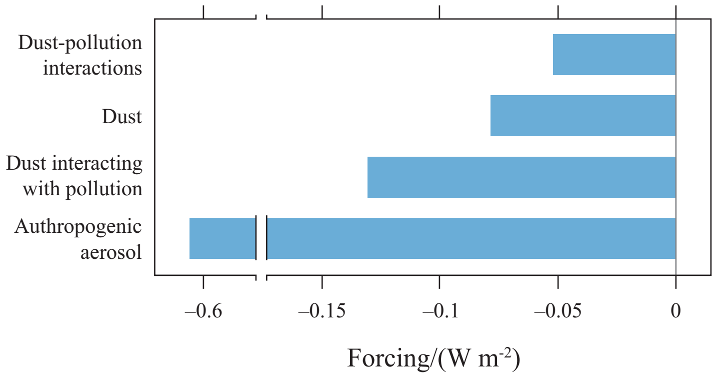

FIGURE 15.10 Direct radiative effect of dust–pollution interactions. Global mean top of the atmosphere forcing of the dust–pollution interactions; this is in comparison with the mineral dust forcing from the ECHAM/MESSy atmospheric chemistry climate model simulation excluding and including the dust–pollution interactions and the anthropogenic aerosol forcing. The coefficients of variation of the interannual variation are (from top to bottom) 7%, 6%, 5%, and 2%.

Source: Klingmüller et al. (2019).

Ozone

Ozone is the third most crucial GHG responsible for climate warming after CO_2 and methane, although its concentrations are extremely low, roughly 0.0012% of the total atmospheric composition (Al-Kallas et al. 2021). Ozone forms a protective cover in the upper atmosphere (stratosphere) and shields Earth from harmful ultraviolet rays. The concentration of chlorofluorocarbons depletes the ozone layer by releasing chlorine into the stratosphere, which reacts with ozone and destroys it. Conversely, ozone in the atmospheric layers near Earth's surface (troposphere) is a major air pollutant and climate forcer (Fu and Tian 2019). Several chemical species are considered to be ozone precursors. One established pathway of ozone formation involves the oxidation of VOCs and non-methane hydrocarbons. These chemical agents are photochemically catalyzed by nitrogen (NO_x), carbon (CO and CO_2), and sulfur oxides (SO_x), which result directly from fossil fuel combustion, biomass burning, and volcanic eruptions. The high temperatures in summer are favorable for these reactions. NO_x and SO_x emissions directly contribute to ozone formation via photochemical reactions. An increase in CO_2 indirectly supports ozone buildup by raising the temperature, thereby providing conducive conditions for its production.

Over the MENA region, the ozone concentration is affected by the Asiatic Monsoon system and associated pollution transport (Al-Kallas et al. 2021). A recent study in Saudi Arabia over 2006–2016 reported that the optical depth of ozone increased from 252 to 264 Dobson Units (Hassan et al. 2019). At the same time, SO_2 and NO_2 concentrations increased by 14% and 11%, respectively. This supports the notion that NO_2 and SO_2 directly contribute to the formation of tropospheric ozone. CO_2 increased from 379 to 401 PPM, which could have increased the optical depth of ozone via the corresponding temperature increase. Particularly, northwest Saudi Arabia has exceptionally high ozone levels (approximately 300 Dobson Units) owing to the large clusters of industries, power plants, and oil refiners in this region (Hassan et al. 2019).

NO_x and nitrates

NO_x (NO_2 and NO) emissions primarily generated from fossil fuel combustion in the power and transport sectors play a critical role in atmospheric chemistry via the formation of ozone and nitrate aerosols. The high burden of NO_x is also a concern for hydrogen and ammonia combustion (Berwal, Kumar, and Khandelwal 2021). The effect of NO_x on the formation of ozone is complex and less understood. It varies by season, the topography of the region, the level of human activities, and the distance from the emission source. Near Earth's surface (stratosphere), NO_x aids ozone production via a catalytic effect, whereas it leads to the destruction of the ozone cover in the higher atmosphere (troposphere). Such variations in NO_x and its correlation with ozone make it challenging to ascertain the warming impact on the global climate and air pollution.

Through a different chemical pathway, NO_x participates in aerosol nitrate formation, producing a net cooling effect on the atmosphere. NO_x reactions with non-methane VOCs lead to organic nitrates that can be transported to remote areas from their sources. These nitrates can re-release NO_x back into the atmosphere in these remote areas. Recent studies have found that NO_x emissions have generally declined across the world's megacities but have gradually increased across developing and remote regions, oceans, and background areas (i.e., areas away from NO_x sources). In the Middle East, the source of NO_x is fossil fuel combustion in the power and transport sectors, whereas natural NO_x emissions are low (Lelieveld et al. 2015; Ukhov et al. 2020b). In the past decade, better air quality control and geopolitical factors (e.g., economic disruptions due to conflicts and COVID-19) have led to a drop in overall NO_x emissions from this region. However, the decline in NO_x emissions is not as significant as that in North America and Europe.

SO_x and sulfates

Roughly 10% of global SO_x (mainly SO_2) emissions originate from the Middle East (Ukhov et al. 2020a). The formation of sulfate aerosols, a principal climate forcing agent, results from SO_2 emissions from the oil and gas, shipping, and power sectors, mainly produced by burning HFO in this region. Up to 40% of global SO_2 is emitted from the oil and gas and power industries, including HFO and coal burning. A Greenpeace report states that "Saudi Arabia is the 4th largest SO_2 emitter in the world, and largest in the Middle East. Makkah province is home to the worst hotspots because of this region's polluting oil-based power plants, industries, and refinery facilities." This report is based on NASA's satellite imaging of the world's top SO_2-emitting hot spots (see Figure 15.11). Within 120 km of the Makkah province, there are vast clusters of SO_2 emission sources, including Rabigh, Shoiba, and Jeddah. The oil power plants and refineries in these sites emitted 59% of the country's SO_2 emissions in 2018. This was mainly caused by expanding the capacity of HFO-based power generation and oil refining/consumption and partly due to the slow implementation of stringent emission standards. The Presidency of Metrology and Environment and Royal Commissions are responsible for prescribing and establishing emission standards in Saudi Arabia. However, these regulations are not as stringent as recommended by the WHO, US Environmental Protection Agency, and other global bodies and major countries. There is a strong likelihood that these emission norms may become significantly stringent for Saudi Arabia in the near future.

Figure 15.12 summarizes the mapping of air pollutants and responsible industrial sectors primarily related to energy production and consumption. The discussion in this section shows how closely related these pollutants are to fossil fuel-based energy production, combustion, and air pollution in Saudi Arabia and the surrounding region.

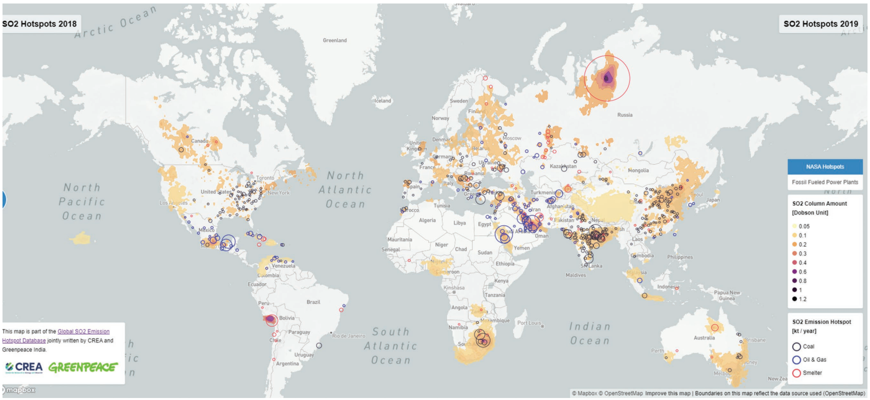

FIGURE 15.11 A global catalog of large SO2 sources and emissions. These data are a part of Multi-Decadal Sulfur Dioxide (SO2) Climatology from Satellite Instruments (MEaSUREs-12-0022 project).

Source: Fioletov et al. (2022); https://disc.gsfc.nasa.gov/datasets/MSAQSO2L4_2/summary.

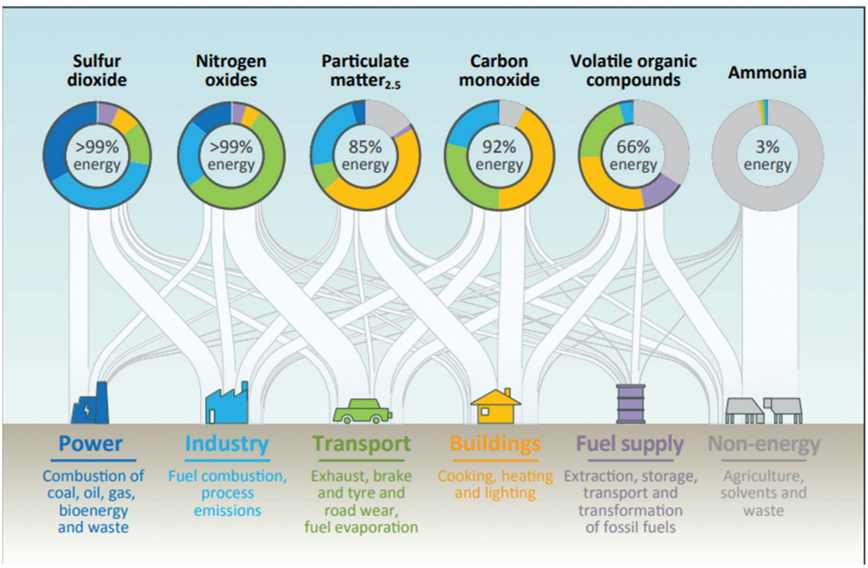

FIGURE 15.12 Selected primary air pollutants and their sources.

Source: OECD (2016).

The potential leak of molecular hydrogen from a large-scale hydrogen infrastructure is discussed in the following section. This section also explains the impact of switching from fossil fuels to hydrogen and its vectors on various emissions.

Potential impact of a large-scale global hydrogen economy on climate change and air quality

An unprecedented worldwide effort is underway to create a global hydrogen economy to accelerate the energy transition toward low-carbon energy choices, with the Paris Agreement listing hydrogen as a critical energy vector for mitigating climate change (Rogelj et al. 2018a). The role of hydrogen can be derived from the global carbon budget as well as from CO_2 and non-CO_2 emission mitigation requirements.

According to AR6, the global temperature rise due to human activities from 1850–1900 to 2010–2019 was between 0.8 and 1.3°C (best case 1.07°C). Historical CO_2 emissions in the same period were 2390 ± 240 gigatonnes. The allowed future (from January 1, 2020 to net-zero) surface temperature increase corresponds to 0.43°C of surface warming by 2050. The remaining carbon budget for curtailing climate warming to 1.5°C is estimated to be 500 and 400 gigatonnes for the 50th and 67th percentiles, respectively. However, this remaining carbon budget could vary by ±220 gigatonnes depending on the level of non-CO_2 emission cuts achieved (referred to as non-CO_2 emission uncertainty in AR6 by WGIII; Allan et al. 2021).

The role that hydrogen can play in a future global energy system is ultimately tied to its implementation rate and proportion of final energy demand. There is considerable variability in the projection of hydrogen in the global energy share depending on the climate target (see Figure 15.13). It could rise to 24% under the 1.5°C goal and increase even further if carbon capture and storage becomes limited (Ocko and Hamburg 2022a; Oshiro and Fujimori 2022). For illustration, we

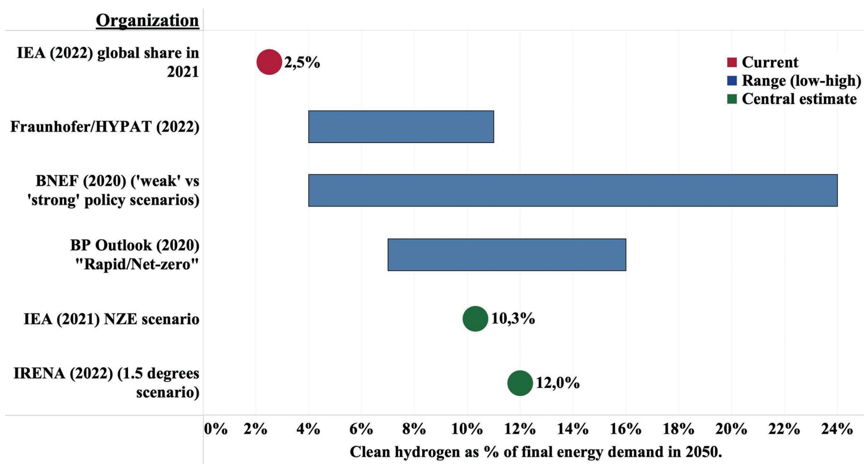

FIGURE 15.13 Share of global clean hydrogen supply (2020 vs. 2050).

Source: Authors based on IEA (2021, 2022), Riemer et al. (2022), Evans and Gabbatiss (2020), and IRENA (2022).

use estimates by various international organizations and research institutions like Fraunhofer.

The IRENA (2022) estimates a capacity of 660 million tonnes of hydrogen (12% of final energy demand) by 2050. Of this capacity, green hydrogen (400–500 million tonnes) and blue hydrogen (120–280 million tonnes) will constitute most of the production by 2050. This amount of green hydrogen would require 3–4 TW of an electrolyzer and 4.5–6.5 TW of renewal energy capacities. Hydrogen-dedicated renewables would be 15%–25% of the 27 TW of renewable energy slated to come online by 2050. For blue hydrogen, a reforming capacity of 120–280 million tonnes is needed, which will require CO_2 storage facilities of 1–2.5 GW/year. The 660 million tonnes of annual hydrogen production by 2050 would allow 7 gigatonnes of avoided CO_2/year, leading to 80 gigatonnes of CO_2 avoided. Decarbonization via hydrogen would provide nearly 20% of the 400-gigatonne carbon budget.

How this scale of hydrogen infrastructure will affect global emissions is not understood. Additionally, the ±220 gigatonne budget from non-CO_2 that could increase or decrease the burden of achieving the net-zero target is rarely considered in these calculations. This significant level of uncertainty must be addressed. Hence, reductions in other GHGs (methane, nitrous oxide, and ozone) and SLCFs (ozone precursors and aerosols) must be considered for a holistic understanding of the required hydrogen supply by 2050.

Hydrogen leak: a challenge for large-scale hydrogen infrastructure

Hydrogen is one of the smallest molecules that can easily leak into the atmosphere. A critical factor is the leakage rate from its supply chain. Hydrogen is a highly potent indirect GHG that acts on time scales (of a few decades) relevant to meeting the Paris goals. Only a few studies have focused on hydrogen as a climate or atmospheric chemistry change agent (Ocko and Hamburg 2022a, 2022b). This insufficient scientific knowledge makes the impact of the perceived large-scale hydrogen energy systems uncertain in multiple aspects. These aspects include the range of leakage rates of molecular hydrogen from the global energy infrastructure, emission types, and corresponding factors. There is also a lack of scientific understanding of atmospheric chemistry. This deals with hydrogen's reactions with other air-bound chemical species (from anthropogenic and natural sources) as well as interactions with stratospheric ozone (Cooper et al. 2022; Department for Business Energy and Industrial Strategy 2019). Various studies have calculated lower and upper bounds of molecular hydrogen leaks from energy systems. At the lower end, a 0.2%–0.5% leak is considered to be close to current hydrogen emissions from fossil fuel-based combustion systems (Cooper et al. 2022) [77]. The upper bound of hydrogen leaks could be anywhere from 10% to 20% (Derwent et al. 2020; Ocko and Hamburg 2022a, 2022b).

The atmospheric chemistry of hydrogen is illustrated in Figure 15.14. The soil removes up to 70%–80% of hydrogen from diffusion and bacterial action.

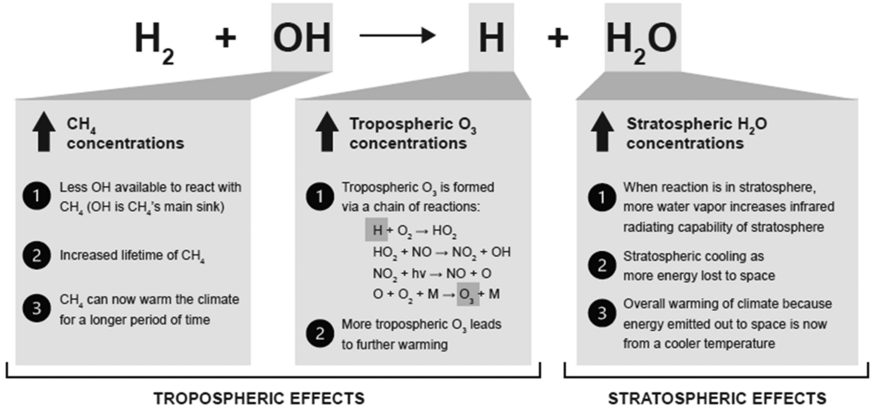

FIGURE 15.14 Effects of hydrogen oxidation on atmospheric GHG concentrations and warming.

Source: Ocko and Hamburg (2022b).

Approximately 20%–30% of hydrogen reacts with the hydroxyl radical present in the atmosphere, resulting in various consequences for the troposphere and stratosphere. Hydroxyl radical is the primary sink for methane in the troposphere; when hydrogen reacts with it, its abundance in the atmosphere decreases. Consequently, less hydroxyl radical is available for reacting with methane and acting as a sink for it, ultimately rendering methane with longer atmospheric lifetimes. This effect accounts for roughly half of the indirect global warming associated with hydrogen.

Additionally, a series of hydrogen oxidation reactions give rise to tropospheric ozone, accounting for 20% of hydrogen's indirect global warming. The remaining 30% of hydrogen's climate impacts come from its actions in the stratosphere. Some studies suggest that reducing atmospheric pollutants (that act as ozone precursors) will ultimately reduce surface or tropospheric ozone, which is desirable. On the contrary, hydrogen may interact with stratospheric ozone via water vapor-catalyzed reactions, leading to its depletion. The effect of the loss of stratospheric ozone could accelerate the impact of methane and surface ozone on global warming. Many complex and interdependent possibilities arise from the increased presence of hydrogen in atmospheric layers. The consequences of such atmospheric chemistry interactions on climate and air quality are unknown. Nonetheless, a high leak rate could reduce the climate benefits driven by hydrogen's inclusion as a decarbonization vector.

Ocko and Hamburg (2022a, 2022b) estimated hydrogen's impact on the climate by comparing its leakage with that from avoided emissions of fossil fuel technoloagies. The warming potential was based on hypothetical hydrogen leakage scenarios in future hydrogen systems ranging from 1% to 10%. They juxtaposed these leakage rates with potential hydrogen demand scenarios for 2050 and estimated possible warming compared with the avoided GHG emissions from fossil fuel technologies.

TABLE 15.1 Hydrogen and methane emissions (in kg), deploying 1 kg of either green or blue hydrogen based on best- and worst-case leak rates.

		Best-case leaks	*Worst-case leaks*
		Hydrogen and methane: 1%	*Hydrogen: 10%; Methane: 3%*
Hydrogen (green and blue)	Produced	1.01	1.11
	Consumed	1	1
	Emitted	0.01	0.11
Methane (blue only)	Produced	3.06	3.44
	Consumed	3.03	3.33
	Emitted	0.031	0.103

Source: Ocko and Hamburg (2022b).

Assumption: three times the mass of hydrogen is needed in the form of methane to use methane as a feedstock for hydrogen production.

Emissions from building the hydrogen infrastructure and inefficiency in carbon capture and storage were not considered in their study. The outcomes were found to be highly variable depending on the choice of production method. Table 15.1 lists the assumptions of Ocko and Hamburg's study regarding hydrogen leakage from the green route and hydrogen and methane leakages from the blue route.

Figure 15.15 shows the estimated relative warming impact of replacing fossil fuel technologies with green or blue hydrogen over time. In the blue hydrogen case, the high leakage of hydrogen and methane scenario (1% and 3%, respectively) turned out to be worse than that using fossil fuel technologies. Green hydrogen with a 10% hydrogen leak was nearly equivalent to the blue hydrogen best-case scenario with low leaks of both hydrogen and methane (1%). The overall best-case scenario involved assuming a low leak with green hydrogen (1%) that virtually eliminated all emissions (compared with fossil fuel-based technologies) at all time scales. It is prudent to note that the assumptions regarding methane in the blue hydrogen case could be lower than this study assumes. Hence, for such scenarios, the climate benefits would be much higher than depicted here. Nonetheless, the analysis provides directional guidance on how hydrogen and methane leaks from the hydrogen infrastructure could benefit the climate.

The estimated long-term temperature response to a level of hydrogen demand of 800 Tg or million tonnes (i.e., roughly 25% of the final energy demand in 2050) could give rise to approximately 0.1°C of warming in the high hydrogen leak scenarios (see Figure 15.16). However, variability is very high owing to uncertainties at many levels. Considering the allowed future (from January 1, 2020 to net-zero) surface temperature increase (0.43°C of surface warming by 2050), the 0.1°C potential contribution from the hydrogen infrastructure is appreciable.

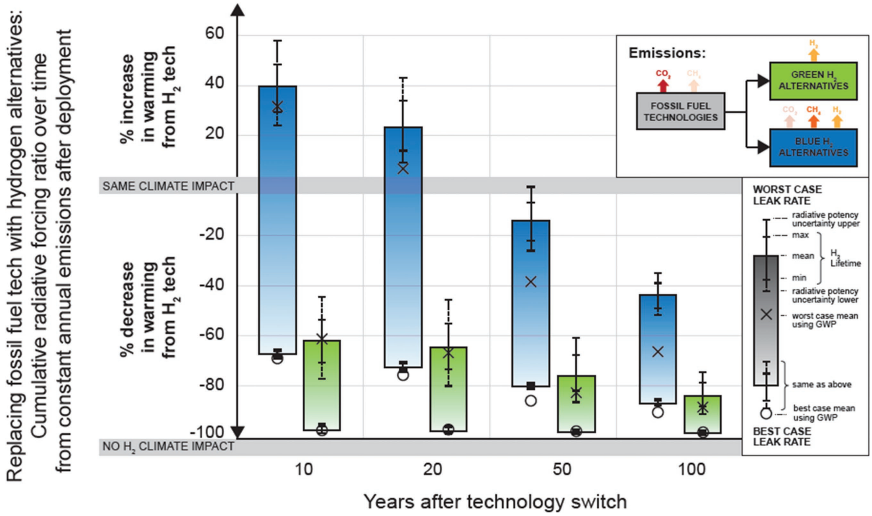

FIGURE 15.15 Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for a generic case. A cumulative RF ratio for annually deploying 1 kg of hydrogen versus annually avoided fossil fuel emissions is used as a proxy for the relative warming impacts. Emissions from hydrogen alternatives are hydrogen for green hydrogen and hydrogen and methane for blue hydrogen. Emissions from fossil fuel technologies are CO_2, estimated at 11 kg CO_2 avoided per 1 kg hydrogen deployed, based on estimates from the Hydrogen Council (2017). Emissions of hydrogen and methane include a range of plausible leak rates from 1% (best case) to 10% (worst case) per unit hydrogen deployed for hydrogen and from 1% (best case) to 3% (worst case) for methane. The height of each bar corresponds to the range of leakage. Error bars represent uncertainties in both hydrogen's soil sink and lifetime (solid lines) as well as uncertainties in the radiative effects of hydrogen and CO_2 (20%; dashed lines). The corresponding GWP results (only difference is pulse emissions rather than the constant emission rate are considered) are shown using "x" and "o" markers.

Source: Ocko and Hamburg (2022b).

Air pollution via the hydrogen value chain

This section discusses those SLCF emissions that constitute essential air pollutants from the hydrogen supply chain. A large-scale hydrogen value chain can affect the climate in two main ways. First, it can reduce the SLCF-like aerosols (PM) that cool the climate. Second, it can increase SLCFs such as ozone precursors (e.g., SOx, NO_x, CO, and UHC) that warm the climate. As a large-scale hydrogen infrastructure is under development, a reliable inventory of SLCF emissions for most of the hydrogen value chain is lacking. Further, studies of the

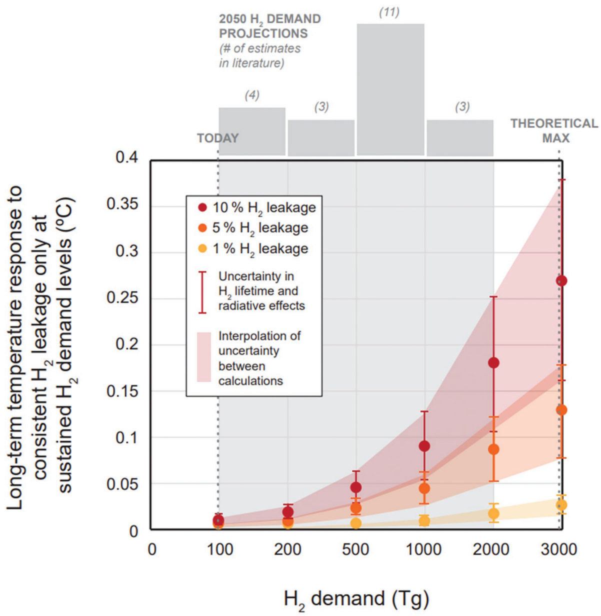

FIGURE 15.16 Long-term temperature responses (in °C) to different levels of hydrogen leakage based on sustained hydrogen demand levels in Tg (1 Tg = 1 million tonnes). The red, orange, and yellow markers and shading represent leakage levels of 10%, 5%, and 1%, respectively. Uncertainty is based on the uncertainty of both hydrogen's soil sink and, therefore, lifetime (20%) as well as hydrogen's radiative effects (20%). The markers indicate calculations and shaded regions represent interpolation. The histogram and shaded gray area characterize projections of hydrogen demand for 2050 in the literature. Depending on the scenario and source, projections for future hydrogen demand range from 100 to 210 Tg by 2030 and from 130 to 1370 Tg by 2050. Of the 21 published estimates for hydrogen demand in 2050, the average is 590 Tg (median is 570 Tg). The theoretical max is an estimate based on using hydrogen to supply total final energy demand globally in 2050 based on decarbonization scenarios. For example, the theoretical maximum from the Hydrogen Council (2017) and BloombergNEF (2020) estimates are 3055 and 2900 Tg, respectively.

Source: Ocko and Hamburg 2022b.

air pollution aspects of the hydrogen value chain are scarce (Department for Business Energy and Industrial Strategy 2019). The vagueness concerning SLCF emissions from hydrogen's value chain can increase the uncertainty of our climate warming estimates. While hydrogen is a clean fuel for most end-use applications such as fuel cells, GHG and air pollutant emissions occur throughout its value chain.

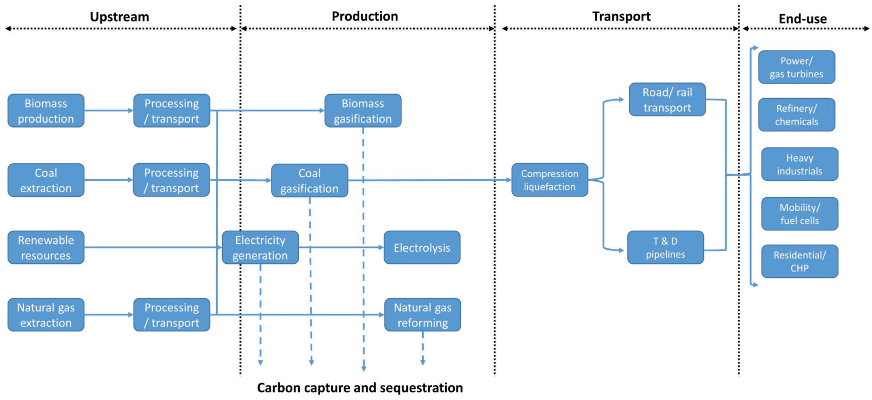

FIGURE 15.17 Illustration of the hydrogen energy chain.

Source: Adapted from Department for Business Energy and Industrial Strategy (2019).

Figure 15.17 illustrates the hydrogen value chain with the upstream and production processes, transport, storage, and end-use applications as the main stages. These stages extensively vary by the nature of upstream processes or feedstock (e.g., coal, petroleum residue, biomass, natural gas, or water), production process (e.g., gasification, reforming, or electrolysis), and type of energy input (e.g., fossil fuel-based, renewable, or hybrid). The transport and end-use application stages are agnostic of the hydrogen production method; however, some SLCF emissions also occur during these stages: T&D: transportion and distribution; CHP: combined heat and power.

Hydrogen's impact depends on the specificities of the chemical species or forcing agent emitted from the value chain. Coal, vacuum residue or biomass gasification, and steam methane reforming (SMR) are prone to causing heavy pollution (PM, SO_x, CO, VOCs, NO_x, trace metals). Emission data related to this are scarce (Department for Business Energy and Industrial Strategy 2019; Oshiro and Fujimori 2022; Sun et al. 2019). SMR and autothermal reforming with carbon capture can reduce CO_2 emissions. However, the remaining air pollutants may not change or may increase due to the use of additional power for carbon capture.

SLCF emissions can be associated with infrastructure buildup, water desalination, and materials recycling during the electrolysis process. The emission intensity of the electricity grid could also be a source of GHG and SLCF emissions, if not fully renewable-based.

The geological storage of hydrogen is not at a high-technology readiness level and air pollution aspects are uncertain. Moreover, the available data on pollutant emissions from different transportation and distribution modes are unreliable.

On the application side, hydrogen fuel cells reduce the emissions of the most harmful pollutants. Nitrous oxide and NO_x pose challenges for most combustion systems (e.g., gas turbines, boilers, internal combustion engines) burning hydrogen or ammonia (although both are carbon-free) (Lewis 2021). In gas turbines, the natural gas and hydrogen blending ratio is a determinant, although many emissions are reduced except for NO_x. If hydrogen is converted into ammonia or methanol, then lifecycle emissions must be considered for certain applications. This discussion could help identify suitable technologies that minimize GHG and SLCF emissions from the hydrogen value chain.

Depicting climate change and air pollution scenarios concurrently: Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs)

The following section examines the climate trajectories that could mitigate global warming due to the GHGs and SLCFs produced by air pollution. The IPCC's AR6 broadens the conceptual framework of five shared SSPs[1] to forecast future climate emission scenarios (Allan et al. 2021; Fujimori et al. 2018; Rao et al. 2017). These five future climate scenarios are sustainability (SSP1), middle-of-the-road pathway (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil fuel development (SSP5; O'Neill et al. 2017), as shown in Figure 15.18.

The RCPs[2] are the trajectories of GHG concentrations used for climate modeling in the IPCC's Fifth Assessment Report (Field et al. 2014). RCPs are classified based on limiting global RF from all sources in the target year of 2100. RCPs 1.9, 2.6, 4.5, 7, and 8.5 respectively represent the trajectory of the RF reduction to these values (in W/m^2) by 2100.

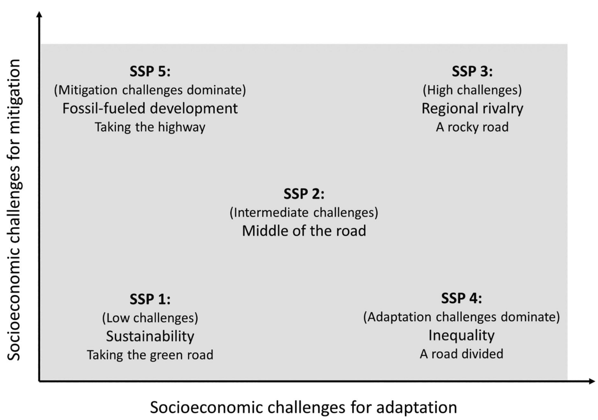

FIGURE 15.18 Five SSPs represent different combinations of the mitigation and adaptation challenges.

Source: O'Neill et al. (2017).

Exploring global warming trajectories using SSP/RCPs

In AR6, these five SSP scenarios are coupled with potential mitigation trajectories in the RCPs (see Figure 15.19a). According to the WGI report of AR6, to achieve the goal of 1.5 or 2°C of warming, immediate and massive cuts in GHGs must be made. SSP1–1.9 and SSP5–8.5 are at opposite ends of the spectrum, as the former leads to negative emissions by 2050 and the latter is the worst-case scenario. Figure 15.19b, borrowed from the World Bank's Climate Change Knowledge Portal (Economics of Climate Change Project 2015), forecasts the most important anthropogenic emissions from 2015 to 2100 based on the SSP/RCP criterion of the IPCC's AR6 report. The emissions of CO_2 and non-CO_2 GHGs (methane and nitrous oxide) are shown along with those of a critical SLCF (SO_2). The total (from all sources) and division of the observed temperature rise due to CO_2/non-CO_2 GHGs as well as aerosol and land use are also shown.

As shown in Figure 15.19, SSP1–1.9 is the most ambitious SSP/RCP combination for limiting global warming as envisioned in the Paris Agreement, well below 2°C compared with the preindustrial temperature (Nazarenko et al. 2015). SSP1–1.9 was introduced after the Paris deal since none of the other SSP/RCP combinations were compatible with its aspirational climate goals. SSP1–1.9 requires global CO_2 levels to drop by 25% and 50% by 2030 and 2035, respectively. This is a highly aggressive trajectory considering the current pace of international climate action efforts. The European Union, United Kingdom, and United States have declared 50% cuts by 2030. Saudi Arabia recently updated its NDC to aim for roughly 39% CO_2 emissions (2019 baseline) by 2030 (Alsarhan and Zatari 2022). If a sufficient number of countries commit to cutting emissions by 50% by 2030, achieving the SSP1–1.9 scenario is possible. The next best scenario (SSP1–2.6) demands a 50% cut in emissions by 2050; however, in this case, the 1.5°C goal will be breached in the second half of the 21st century. SSP1 with RCP2.6 and SSP4 with RCP4.5 can achieve those CO_2 emission cuts in this century. However, warming is unlikely to be contained to 1.5°C or 2°C. Among the other SSPs, SSP2 with RCP4.5 overshoots the 2°C target, which is highly insufficient. The AR6 report mentions that SSP5–8.5 and SSP3–7.0 are unlikely to happen since the world is phasing out its use of coal.

Climate change and air pollution through the lens of the SSP/RCP scenarios

SSPs cover the high- and low-CO_2 pathways by making various assumptions about air pollution control. Figure 15.20, sourced from IPCC AR6, provides insights into the effects of SLCFs on the global surface temperature and air pollution levels. The projections are in conjunction with the SSP scenario for the near and long term. Air quality is tracked using atmospheric levels of $PM_{2.5}$ and tropospheric ozone. The concentrations of $PM_{2.5}$ and ozone are estimated using the state-of-the-art

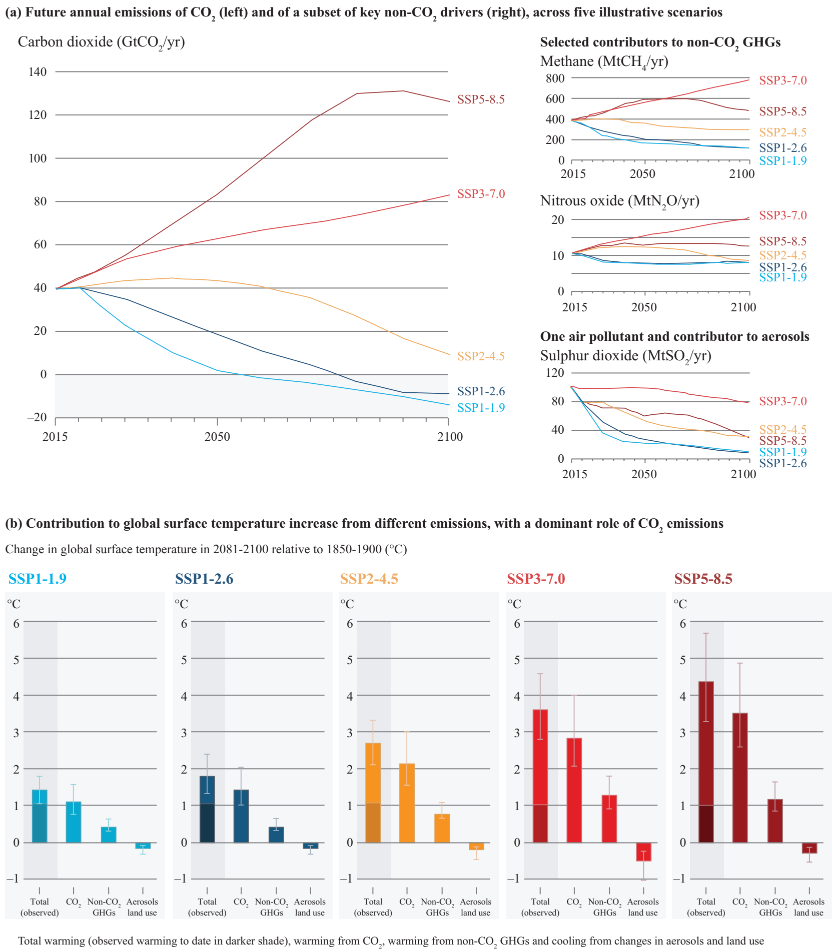

FIGURE 15.19 Annual anthropogenic (human-caused) emissions over 2015–2100. The following are shown: emission trajectories for CO_2 from all sectors ($GtCO_2$/year) (left graph) and for a subset of three key non-CO_2 drivers considered in the scenarios—methane (Mt of methane/year), nitrous oxide (Mt of nitrous oxide/year), and SO_2 (Mt of SO_2/year)—contributing to anthropogenic aerosols in panel (b). (b) demonstrates the change in the global surface temperature (°C) in 2081–2100 relative to 1850–1900 given the warming contributions by groups of anthropogenic drivers and by scenario, with an indication of the observed warming to date. The bars and whiskers represent median values and the very likely range, respectively. Each scenario bar plot represents total global warming (°C); warming contributions from changes in CO_2 and non-CO_2 GHGs; and net cooling from other anthropogenic drivers ("aerosols and land use" bar).

Source: Reproduced from the Economics of Climate Change Project (2015).

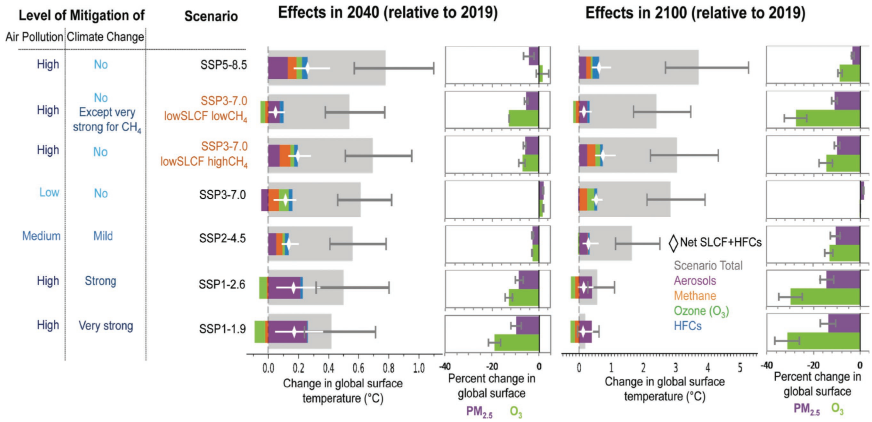

FIGURE 15.20 Box TS.7, Figure 1 | Effects of short-lived climate forcers (SLCFs) on global surface temperature and air pollution across the WGI core set of Shared Socio-economic Pathways (SSPs). The intent of this figure is to show the climate and air quality (surface ozone and particulate matter smaller than 2.5 microns in diameter, or PM2.5) response to SLCFs in the SSP scenarios for the near and long-term. Effects of net aerosols, tropospheric ozone, hydrofluorocarbons (HFCs; with lifetimes less than 50 years), and methane (CH4) are compared with those of total anthropogenic forcing for 2040 and 2100 relative to year 2019. The global surface temperature changes are based on historical and future evolution of effective radiative forcing (ERF) as assessed in Chapter 7 of this Report. The temperature responses to the ERFs are calculated with a common impulse response function (RT) for the climate response, consistent with the metric calculations in Chapter 7 (Box 7.1). The RT has an equilibrium climate sensitivity of 3.0°C for a doubling of atmospheric CO_2 concentration (feedback parameter of –1.31 W/m²/°C). The scenario total (gray bar) includes all anthropogenic forcings (long- and short-lived climate forcers, and land-use changes). Uncertainties are 5%–95% ranges. The global changes in air pollutant concentrations (ozone and PM2.5) are based on multimodel Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations and represent changes in five-year mean surface continental concentrations for 2040 and 2098 relative to 2019. Uncertainty bars represent inter-model ±1 standard deviation. {6.7.2, 6.7.3, Figure 6.24}.

Source: Reproduced with permission from IPCC. Permission to reuse must be obtained from the rightsholder. Chapter, figure and section numbers referred to in this legend refer to the IPCC report (Arias et al. 2021).

CMIP6 multi-model (Iturbide et al. 2020). The future (2040 and 2100) RF effects of net aerosols, tropospheric ozone, hydrofluorocarbons, and methane are compared with total anthropogenic forcing in 2019. The impact of SLCF emissions on

Earth's surface temperature is tied to how the warming and cooling SLCFs evolve. The magnitude of cooling aerosols is the most uncertain in the future climate projections. Warming due to SLCFs and halocarbons falls in the range of 0.06–0.35°C in 2040 relative to 2019. This near-term warming is similar across the SSPs primarily due to the response to the competitive effects of warming (methane and ozone) and cooling (aerosols). By contrast, the SSP projections for long-term warming (2100) vary significantly. Overall, SLCFs may warm the climate in the range of 0.0–90.3°C by 2100 (relative to 2019) under SSP1–1.9 and SSP1–2.6. The effects of warming due to halocarbons will remain low due to adherence to the Montreal Protocol and many national mitigation plans.

SSP1 and SSP5, which include substantial pollution control, project a decline in emissions of ozone precursors (excluding methane). However, SSP5, which envisions high fossil fuel utilization for growth, has no climate benefits. The SSPs that assume significant decarbonization also lead to strong pollution control (e.g., SSP1–1.9 and SSP1–2.6). Methane declines rapidly in SSP1–1.9 and SSP1–2.6. Nonetheless, even under the best-case scenario (SSP1–1.9), the reduction in air pollution is insufficient to raise air quality to the level prescribed by the WHO (Masson-Delmotte et al. 2021). Waste management and clean energy policies are thus required in addition to climate policies. SSP3–7.0, which does not mitigate climate change and offers only weak air pollution control, can lead to a high degradation in air quality. PM levels are expected to peak by 2050 in parts of Asia, whereas surface ozone is projected to worsen in all continents until 2100.

A "desirable" sustainable climate trajectory (SSP1–RCP1.9/2.6) for the Arabian Peninsula

Geographically, Saudi Arabia occupies 80% of the Arabian Peninsula; the remaining 20% includes Kuwait, Oman, Qatar, the United Arab Emirates, Yemen, and some parts of Iraq and Jordan. All these countries are primarily oil and gas economies with heavy fossil fuel use and similar sectoral emissions. The authors recommend SSP1–1.9 as the guiding climate pathway for this region. The AR6 reports lay out the trajectories of the climate scenarios based on the latest climate models. The novel AR6 WGI Interactive Atlas allows for a flexible spatiotemporal analysis of both data-driven climate change information and assessment findings (Gutiérrez et al. 2021; Iturbide et al. 2021). The trajectories of anthropogenic CO_2 (Figure 15.21), $PM_{2.5}$ (Figure 15.22), and ozone (Figure 15.23) are reproduced from the IPCC Interactive Atlas for the Arabian Peninsula. For CO_2, the SSP1–1.9 projections are plotted in Figure 15.21. Because the SSP1–1.9 projections for $PM_{2.5}$ and ozone are unavailable from the IPCC Interactive Atlas, we plot the SSP1–2.6 trajectories of these two climate forcers. The CMIP6 climate model-derived trajectories show the upper bounds of the allowable GHG and SLCF emission budgets and associated air quality benefits for this region. Climate action and pollution mitigation policies can then be aligned with these emission trajectories.

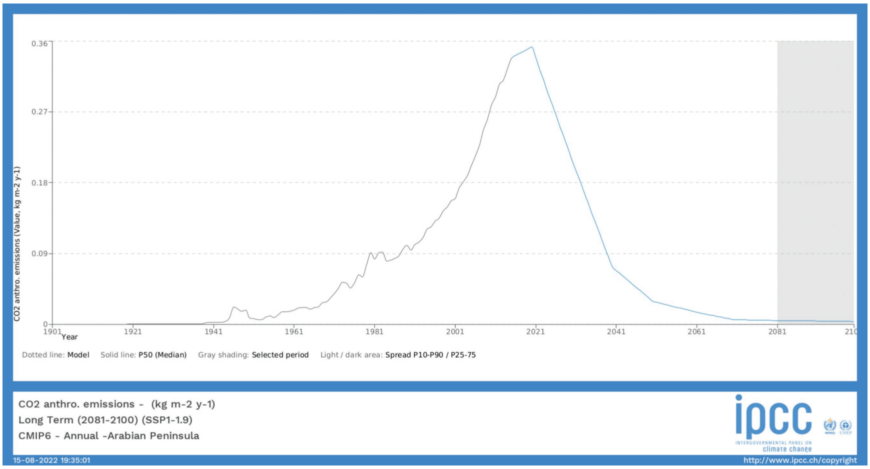

FIGURE 15.21 CO_2 emission trajectory for the Arabian Peninsula in the SSP1–1.9 scenario.

Source: Gutiérrez et al. (2021) and Iturbide et al. (2021). Reproduced from IPCC AR6 WGI Interactive Atlas.

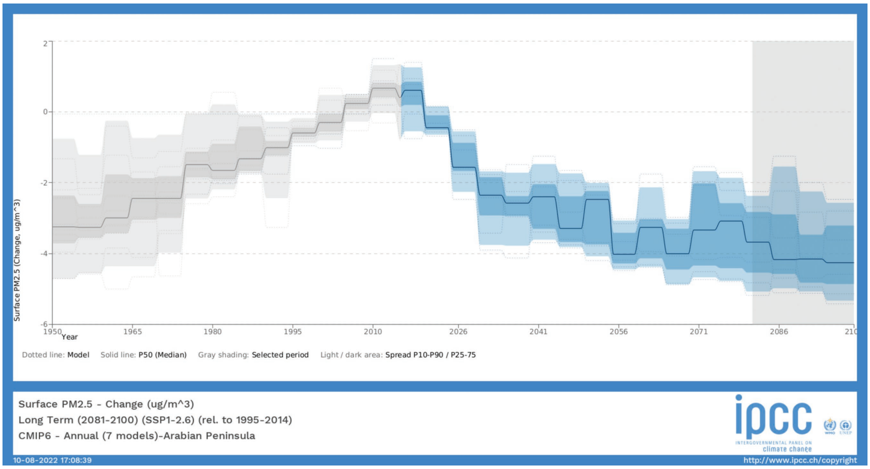

FIGURE 15.22 $PM_{2.5}$ emission trajectory for the Arabian Peninsula in the SSP1–2.6 scenario.

Source: Gutiérrez et al. (2021) and Iturbide et al. (2021). Reproduced from IPCC AR6 WGI Interactive Atlas.

As we replace fossil fuels with natural gas, hydrogen, and ammonia, emissions of air pollutants will be drastically impacted. This impact could be either beneficial or detrimental to global warming since RF from these pollutants can be either positive or negative. Table 15.2 lists fossil fuels and shows their propensity to form air pollutants critical for climate change. Although coal is the worst fossil fuel worldwide, only the combustion of oil and natural gas is relevant for Saudi Arabia

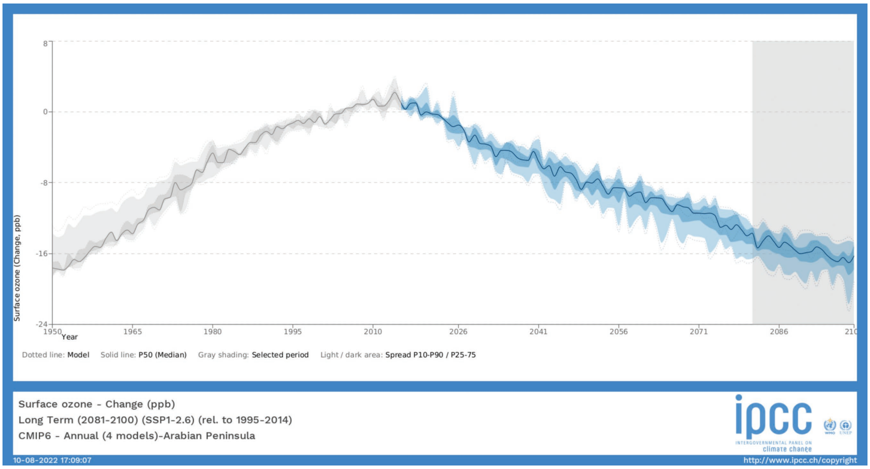

FIGURE 15.23 The ozone emission trajectory for the Arabian Peninsular in the SSP1–-2.6 scenario.

Source: Gutiérrez et al. (2021) and Iturbide et al. (2021). Reproduced from IPCC AR6 WGI Interactive Atlas.

since it does not use coal. All the pollutants listed are reclassified based on their impact on ozone and PM. Switching to hydrogen and ammonia lowers most of these pollutants' emissions. However, net RF eventually increases with a decrease in PM. Hence, an inventory of air pollutants is essential for quantifying the impact of introducing hydrogen and ammonia in relevant economic sectors (energy, transportation, and heavy industries). Further, the precise level of hydrogen needed to offset key air pollutants must be considered before setting realistic net-zero goals. Climate-cooling aerosols can be significantly reduced due to hydrogen combustion or utilization in fuel cells, reducing aerosols' cooling effect. Consequently, GHG reduction must be increased in amounts proportionate to the loss of aerosol cooling.

Figure 15.24 summarizes the main arguments of the chapter and presents the steps to achieve the net-zero and air quality goals, with a large-scale hydrogen economy playing an important supporting role.

Recommendations and conclusions

Synchronize the circular carbon economy with air pollution control policies

The IPCC's AR6 in 2021 emphatically conveys that CO_2 and non-CO_2 climate forcers must be targeted to address short- and long-term global warming. While the world is focused on reducing CO_2 and methane emissions, SLCFs stay under the radar, with aerosols being the most prominent SLCFs. The aerosols generated from fossil fuel combustion, forest fires, and other natural emissions produce a cooling effect instead of a warming one. Hence, they are the greatest source

TABLE 15.2 Fuels and their propensity to generate climate-impacting emissions of air pollutants from fossil fuels (production and combustion).

Chemical active gases or aerosols	*Impact on particulate matter*	*Impact on ozone*	*Coal combustion*	*Oil combustion*	*Natural gas combustion*	*Hydrogen/ Ammonia combusion*
GHGs						
Carbon dioxide (CO_2)	X	X	H	H	M	L
Methane (CH_4)	X	√	M	M	H	L
Nitrous oxide (N_2O)	√	√	H	H	M	L
Halogenated compounds (X_{halo})	X	X	H	M	L	L
Stratospheric vapor (H_2O_s)	X	√	H	H	M	M
Terrestrial ozone (O_3t)	X	√	H	H	M	M
Stratospheric ozone (O_{3s})	X	√	H	H	M	M
Molecular hydrogen (H_2)-leakage	X	√	L	L	L	H
Ammonia slip (NH_3)	√	X	L	L	L	M
SLCFs						
Black carbon (BC)	√	X	H	H	L	L
Organic carbon (OC)	√	X	H	H	L	L
Primary organic aerosols (POA)	√	X	H	H	L	L
Secondary organic aerosols (SOA)	√	X	H	H	L	L
Aerosol–cloud interaction	√	X	H	H	L	L
Albedo changes induced by BC deposition on snow	√	X	H	H	L	L
Nitrate (NO_3) from nitrogen oxide emissions (NOx)	√	√	H	H	H	L
Sulfate (SO_4) from sulfur oxide emissions (SOx)	√	√	H	H	M	L
Non-methane volatile organic compounds (NMVOC)	√	√	H	M	M	L
Carbon monoxide (CO)	X	√	H	M	M	L

Emission propensity is as follows: H: high; M: medium; L: low

Source: Authors.

The non-CO_2 emissions can be broadly divided into PM and ozone. Using hydrogen and ammonia can reduce most air pollutants from combustion markedly.

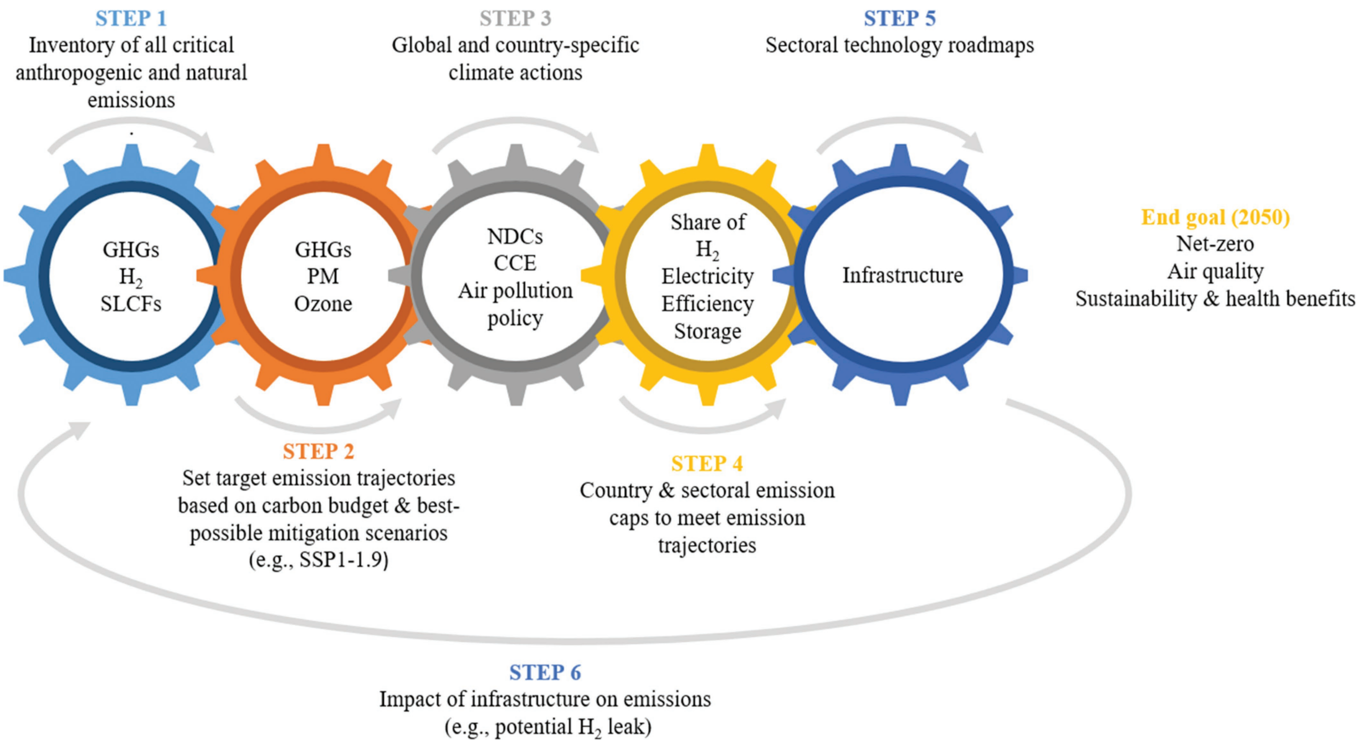

FIGURE 15.24 Comprehensive climate change mitigation and air quality improvements. The supportive role of hydrogen in achieving climate, air quality, and health goals is highlighted. A large-scale hydrogen infrastructure may cause hydrogen emissions. Hence, a feedback loop to an emissions inventory is provided to underscore that possibility.

Source: Authors.

of uncertainty in climate warming modeling since their cooling effect is highly variable and largely intractable. The remaining carbon budget of 400 ± 220 gigatonnes to keep warming below 1.5°C by 2050 is also highly uncertain. The ±220 gigatonnes budget uncertainty from non-CO_2 could increase or decrease the burden of achieving the net-zero target. This significant uncertainty must be addressed by conducting scientific studies and improving emission reporting.

Recently, Saudi Arabia updated its target CO_2-equivalent reduction to 278 million tonnes of CO_2-equivalent annually by 2030, nearly doubling its earlier commitment of 130 million tonnes. The country has one of the lowest methane emission intensities globally and is working on programs to minimize fugitive methane emissions from the natural gas supply chain. However, a comprehensive climate policy must consolidate climate action with air pollution controls. With significant anthropogenic PM, NO_x, and SO_x emissions from burning fossil fuels, Saudi Arabia must bring the targeted SLCF reduction under the umbrella of climate policy. A holistic climate policy that builds on circular carbon economy initiatives can complementarily include air pollution mitigation via SLCF controls and encompass the potential environmental impact of a large-scale hydrogen economy.

Create an inventory of SLCF emissions from the conventional fossil fuel-based and potential hydrogen value chain

Hydrogen is often considered to be the missing piece of the energy transition puzzle. However, large-scale hydrogen penetration and its impact on climate change and air quality have not been fully estimated until now. Hydrogen can also be a highly potent indirect GHG; its combustion can lead to harmful pollutants such as NO_x. Conversely, hydrogen applications improve air quality by reducing aerosol formation, leading to more planet warming.

Reductions in all GHGs (CO_2, methane, nitrous oxide, and ozone) and SLCFs (ozone precursors and aerosols) must be carefully considered to ensure a holistic understanding of the required hydrogen supply by 2050. Since a large-scale hydrogen infrastructure has not explored thus far, there is apprehension about global warming being exacerbated by hydrogen leaks from the hydrogen value chain as well as about the uncertainty of SLCF emissions (air pollutants). Countries have built inventories of GHGs such as CO_2 and methane from various sources and sectors; however, such data are unavailable for SLCFs. Precise measurements and estimates of SLCFs and leaks of molecular hydrogen emissions across the hydrogen value chain are therefore critical for quantifying their effects on global warming and air quality.

The technology landscape should be based on emission scenarios and hydrogen penetration

Future climate scenarios from advanced climate models in SSP/RCP combinations present an invaluable tool for focusing on global warming and air pollution concurrently. State-of-the-art climate modeling provides time-varying trajectories of CO_2, methane, PM, and ozone emissions until 2100 across SSP ranges as well as mitigation target scenarios (RCPs). SSP1–1.9 offers guidelines for the most sustainable climate pathway. Such scenarios can help us ascertain the time-bound emission reductions of all critical climate forcers and policy pathways to achieve sustainable economic growth and meet the Paris climate goals.

One way to decipher hydrogen's role is to assume low, medium, and high levels of penetration in the final energy mix to meet a specific carbon budget. The options and trajectories of hydrogen technology can be hypothesized using these assumptions. Irena (2022) estimated hydrogen demand of 660 million tonnes by 2050, including green hydrogen (400–500 million tonnes) and blue hydrogen (120–280 million tonnes). This hydrogen is sufficient to reach the 1.5 °C climate warming target in conjunction with other energy vectors such as electricity and bio-energy.

The technology roadmap targeting the green and blue hydrogen infrastructures must be created based on hydrogen's potential to mitigate GHG and SLCF emissions and address their tradeoffs. This roadmap must also be synchronized with the circular carbon economy and air pollution control roadmaps. The ideal hydrogen technologies for critical sectors and regions could be listed to enable policy actions at the country level. Technology roadmaps could then be formulated in conjunction with a nation's natural resources, prevailing cost functions, and the minimization of the potential of stranded assets.

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Notes

1 SSPs are qualitative descriptions of future demographic changes, human development, economies and lifestyle, policies and institutions, technology, and the environment and natural resources. SSPs allow us to forecast future changes in climate and society to investigate the climate impacts and options for mitigation and adaptation.

2 RCPs are used to build future climate scenarios based on GHG emissions from human activities, depending on the efforts taken to limit such emissions.

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16

HYDROGEN VALUE CHAIN

Critical platform of the energy transition ecosystem

Alexander John Cruz

Introduction

Several recent studies, pilots, and commercial projects show that hydrogen can be used as a fuel, a feedstock, and an energy storage platform. Hydrogen is also envisaged to support and facilitate low-carbon emission strategies for power generation, extractive industries (e.g., mining), and industrial sectors. While hydrogen under ambient conditions is in gaseous form, certain transformation steps are necessary to improve the efficiency of its transport, storage, and utilization. These include its transformation to a different state (of matter) or conversion to another form (chemistry).

As shown in Table 16.1, industry has been using colors to describe artificially generated hydrogen, with each color relating to the energy source and process used for its production (Hydrogen Council 2021a; H2 Industries n.d.). While this scheme does not explicitly allow business leaders and policymakers to quantify the carbon potential of such technologies, they do occasionally refer to these terminologies. This chapter provides a tutorial-type overview of the landscape of hydrogen production technology, describing the basics and critical challenges of each color type (Table 16.1).

First, green hydrogen is produced using renewable energy. An array of techniques are available to produce hydrogen via renewables, including water electrolysis, biomass gasification, pyrolysis, thermochemical water splitting, photocatalysis, supercritical water gasification, and combined dark fermentation-anaerobic digestion (Department of Energy n.d.a). Green hydrogen production is primarily linked to water electrolysis, which splits water into hydrogen and oxygen, yielding hydrogen gas via an electrolyzer. In its simplest form, an electrolyzer is a device comprising positive and negative electrodes, a membrane, pumps, vents, storage tanks, a

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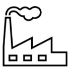
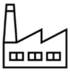
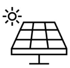
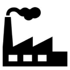
TABLE 16.1 Challenges of hydrogen production technologies

Process	*Description*	*Challenges*
Gray hydrogen 	Steam methane reforming	CO_2 is still emitted in the process (not abated or stored)
Blue hydrogen 	Steam methane reforming, coal gasification, integrated with carbon capture and storage	Cost of capture; availability of adequate subsurface storage capacity
Green hydrogen 	Electrolysis using renewable power (direct or grid-connected)	Availability and cost of renewable energy; water scarcity
Turquoise hydrogen 	Production through methane pyrolysis	Greenhouse gas emissions from the electricity needed to provide the heat for pyrolysis
Pink hydrogen 	Hydrogen production via electrolysis using nuclear power	Cost and availability of nuclear power
Red hydrogen 	High-temperature catalytic water splitting with nuclear power thermal as an energy source	Cost and availability of nuclear power

Source: Droege (2021); H2 Bulletin (2022); Williams Companies (2021).

power supply, a separator (e.g., the membrane), and other ancillary components. Many water electrolyzer technologies are available, such as alkaline, anion exchange membrane, proton exchange membrane, and solid oxide. Alkaline water electrolysis, thanks to inexpensive materials, is available for large-scale applications (Martino et al. 2021). For the hydrogen production process to be tagged as green, the electricity needed to drive the electrolyzer must be sourced from renewable energy (e.g., wind, solar, and hydro).

Second, blue hydrogen is generally produced through steam methane reforming and coal gasification. Carbon capture and storage or sequestration must accompany the hydrogen production process to be considered blue; otherwise, the output is referred to as gray hydrogen. The CO_2 generated in the process is captured and utilized or stored in permanent underground storage in geological formations. In steam methane reforming, methane reacts with steam (water vapor) at a pressure range of 3–25 bar (Chen et al. 2020). When using a catalyst, a material that lowers the activation energy of a reaction, the process produces a gas mixture of hydrogen and other components such as CO_2 and carbon monoxide. In this process, steam is injected at temperatures between 700°C and 1,000°C (Chen et al. 2020); then, CO_2

and other substances are removed via separation processes, leaving only hydrogen for further use. Blue hydrogen from coal gasification is produced by heating coal at elevated temperatures to produce a gas mixture. More than 100 coal gasification plants are in operation globally, such as the Jizan integrated gasification combined-cycle power development in Saudi Arabia (NS Energy n.d.a; Energy & Utilities 2021).

Third, methane pyrolysis employs the thermal decomposition of methane to produce hydrogen and carbon, also known as turquoise hydrogen. Here, CO_2-free hydrogen is generated with solid carbon as the only byproduct. Various strategies can be employed to upgrade solid carbon into profitable carbon-based products to make commercially attractive hydrogen production pathways (Sánchez-Bastardo, Schlögl, and Ruland 2021).

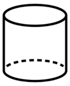
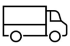
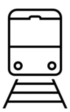
Finally, other colors of hydrogen are produced by using technologies still in the demonstration or pilot stage. For instance, hydrogen production from gasification converts organic or fossil-based carbonaceous materials at temperatures above 700°C with a small amount of oxygen and water vapor. The process yields carbon monoxide, hydrogen, and CO_2. Membranes are then used to collect, separate, or purify the hydrogen from the gas stream. Gasification in the absence of oxygen is called *pyrolysis*. Relatively new technologies such as the thermochemical water-splitting technique use even higher temperatures generated by concentrated sunlight focusing on a reactor tower utilizing mirror “heliostats.” Photocatalytic methods for hydrogen production are achieved through water splitting using solar energy via electron-hole pair generation based on the use of photons and semiconductors (Martino et al. 2021).

Some technologies are in the early R&D stages. For example, fermentation, a biological method used to produce hydrogen, can be classified into direct/indirect photolysis, photo-fermentation, dark fermentation, and carbon monoxide gas fermentation. The natural path of photolysis is a photosynthetic reaction (like the natural process of plants) that uses microalgae combined with solar energy. The water is then separated using cyanobacteria and blue/green algae. The two-step process generates hydrogen and CO_2 (Martino et al. 2021). Photo-fermentation has limitations for industrialization because of the scarce availability of precursor biomaterials and meticulous processes involved in handling biological compounds (Department of Energy n.d.a).

Transportation

Hydrogen transportation, an essential part of the hydrogen value chain (Table 16.2), comprises three fundamental modes: transport as (1) gaseous hydrogen, (2) cryogenic liquid hydrogen, and (3) novel solid or liquid hydrogen carriers. The suitability of these three modes depends on the level of demand and transport distance to be covered (Hydrogen Council 2021b). For distances under 1,500 km, transporting hydrogen in gaseous form via pipelines is generally the most economical choice (Gas

TABLE 16.2 Hydrogen transportation pathways

Transportation pathway	*Description*
Pipelines 	Dedicated hydrogen pipelines or mixed/blended with natural gas in existing gas transport platforms
Marine terminals 	Hydrogen can be distributed via ports or terminals, including liquefied natural gas terminals tailored specifically for transporting hydrogen
Shipping 	Hydrogen transportation over significant distances by ship via liquid or gaseous hydrogen carriers
Truck loading 	Hydrogen transportation by truck in gaseous or liquefied form or via liquid/gaseous hydrogen carriers
Rail 	Transported in gaseous form or via gaseous hydrogen carriers using compressed gas cylinders in tube trailers. Specialized containers exist for transporting hydrogen in liquid form or liquid hydrogen carriers

Source: IRENA (2022).

Infrastructure Europe 2021), but only if an existing pipeline network is readily available for retrofitting and large volumes are being delivered. At lower utilization rates or in the absence of pipelines, delivering compressed gas or liquid hydrogen through lorry and rail transportation modes is the most attractive option. Hydrogen shipped overseas must be in liquid form or transported via a carrier such as a hydrogen derivative (i.e., other than free molecules (H_2)), as this makes it easier to transport, handle, and store and has a form with high volumetric density. The several R&D activities on carbon-neutral hydrogen carriers being carried out are at relatively unadvanced stages of development from a commercial standpoint. Solid carriers such as metal hydrides, a family of metal-containing materials bound to a hydrogen, are already established in several focused applications (e.g., submarines and scooters; H2FC-SUPERGEN n.d.). Liquid organic hydrogen carriers (LOHCs) are another interesting class of carriers that offer none-to-minimal boil-off losses. Mostly comprising oil derivatives, LOHCs can be maintained in a liquid state under ambient conditions (Climate Change Committee 2015). LOHCs are organic compounds that absorb and release hydrogen via chemical reactions, with the toluene/methylcyclohexane (MCH) system a canonical example. Alternatively, hydrogen can also be distributed in fuels such as ethanol, compressed natural gas, and ammonia. Several carbon-neutral scenarios are foreseeable if such products are produced from nonfossil fuel sources (e.g., biomass; Climate Change Committee 2015). A green hydrogen-based ammonia plant capable of producing 1.2 million tons of green ammonia per year is predicted to start construction from 2025, demonstrating the commercial viability of such technologies (Energy & Utilities 2021).

Enabling technologies to transport gas and liquid hydrogen

Transporting hydrogen via pressurized gas is the most viable option owing to the maturity of gas compression technology. The latter has advanced to the point that hydrogen compressors (positive displacement and centrifugal compressors) are now similar to natural gas compressors. After compression, the gaseous hydrogen is usually transported by tube trailers or pipelines. Some initiatives have assessed the current pipeline network for expanding natural gas to hydrogen transport through retrofitting and adopting the existing infrastructure (Climate Change Committee 2015; IOGP 2021). Another pathway is hydrogen blending into natural gas pipelines, which presents an additional opportunity for delivering to existing networks. Pure hydrogen delivery may also be possible, enabled by advanced separation and purification technologies.

Hydrogen transported by trucks is typically hauled in either liquid tanker trailers or tube trailers. Transporting (relatively) small amounts of hydrogen over long distances in this pathway is more economically viable in the absence of a suitable pipeline network (Department of Energy n.d.b). Compressed hydrogen in gas cylinders or gas tubes is compressed at pressures of 200–500 bar. Such tube trailers with steel cylinders can accumulate up to 25,000 liters (200 bar), which amounts to approximately 420 kg of hydrogen (Rödl, Wulf, and Kaltschmitt 2018). Trucking liquid hydrogen over long distances in insulated cryogenic tanker trucks is forecasted to be more cost-effective than trucking gaseous hydrogen, as such trucks carry more hydrogen than gaseous tube trailers (Rödl, Wulf, and Kaltschmitt 2018). Transporting large volumes of liquid hydrogen between countries through subsea pipelines and shipping is also being considered.

The broad challenges of transporting hydrogen—whether via pipeline, trucking, or shipping—include the development of advanced materials to address hydrogen embrittlement, integration of engineering solutions to prevent leakage, proposal of process solutions to maintain hydrogen purity during transport, and development of hydrogen-sensitive and selective sensors for monitoring molecules, among others. Equally importantly, the relative energy intensities and carbon footprint of these transport technologies must be estimated more accurately to calculate the overall emissions of the value chain.

Ammonia handling and transporting

Using ammonia as a hydrogen carrier has recently gained attention given the vast experience of industry in handling (liquifying, storing, and transporting) ammonia compared with hydrogen (ScienceDaily 2020). Another significant advantage of transporting liquid ammonia over liquid hydrogen is its established transportation infrastructure and presence in global markets, particularly the fertilizer market. Moreover, liquid ammonia has higher energy density per volume than liquid hydrogen. Therefore, suppliers can transport it more economically using already available trade ships. Another potential benefit of ammonia transport is the use of long-distance pipelines through a distributed network. The Magellan and NuStar pipelines stretch across hundreds of kilometers to supply ammonia from the natural gas extraction reservoirs to fertilizer-intensive regions in the United States. Indeed, energy losses in ammonia pipelines, rails, and trucks are lower than those in electricity transmission lines when transported over large distances (Royal Society 2020). All these reasons suggest that ammonia is a prime candidate for use in the international renewable energy market. However, one of the disadvantages of using ammonia as a hydrogen carrier is that its reconversion into a functional form or direct utilization can lead to considerable energy losses and achievable purity levels. Giddey and colleagues (2017) estimated the round-trip efficiencies of ammonia using various scenarios in synthesis process conditions, transport, and utilization. Another critical factor is the toxicity of ammonia, which may affect its transport and storage capacity around populated areas (i.e., incurring additional costs and necessitating extra measures; Hydrogen Council 2021b).

Risks associated with transporting liquid hydrogen

One of the main drawbacks of the transportation and storage of liquid hydrogen is that a boil-off occurs in all transportation segments, leading to a net loss in the payload. An estimated 20% and possibly up to 50% of the hydrogen is lost when transferred from a Dewar vessel to another type (HSE n.d.). When transferred from a trailer, the loss is approximately 10% (HSE n.d.). Apart from boil-off losses, other risks include the explosive nature of hydrogen. Cooled to cryogenic temperatures, hydrogen is accompanied by highly dense and cold hydrogen vapor in its liquid phase. The fluid temperature is so low that it may solidify the other nitrogen or oxygen in the air (Gerboni 2016). Mixing air (or oxygen) with liquid hydrogen may result in an explosive mixture. Therefore, a critical part of the delivery process is the transport of the liquid hydrogen from the tank to the receiving end, as the difference in temperature between the ambient and internal environment can be considerable.

Dehydrogenation and storage

As with transport, hydrogen can be stored in its gaseous or liquid form (Figure 16.1). Compressed hydrogen at pressures kept at 200–700 bar in tanks can increase storage density (Andersson and Grönkvist 2019; Zivar, Kumar, and Foroozesh 2021). Liquid hydrogen storage is also a developed technology widely used in industrial applications, as more hydrogen can be stored per unit volume. Owing to their high

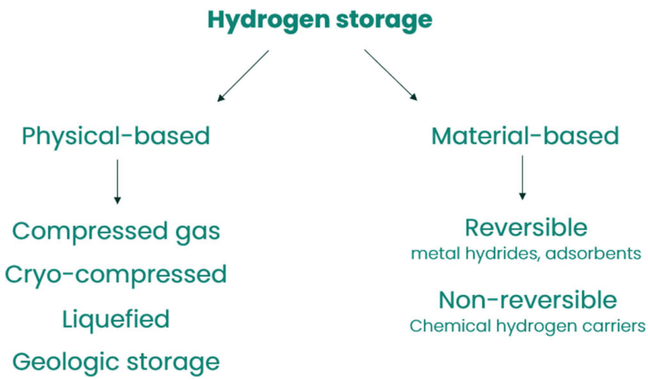


FIGURE 16.1 Hydrogen storage modes.

Source: Authors, adapted from Department of Energy (n.d.a, n.d.b).

discharge rates, compressed or liquid hydrogen storage in tanks is especially appropriate for smaller applications where a local stock of fuel must be readily available. However, pressurized tanks need a high operational cycling rate to be commercially viable (Energy Transition Institute n.d.). If the storage time increases to more than a few days, the capital costs of vessels and compressors become disadvantageous for this technology. R&D is underway to optimize the storage conditions depending on the location of the storage site (factoring in safety and ease of use).

As the hydrogen value chain expands, the importance of bulk compressed hydrogen storage solutions is increasing, primarily at industrial sites (Climate Change Committee 2015). The most mature bulk storage technology compresses hydrogen in large stationary vessels (low pressures) or multicylinder pallets and pressure tubes (medium-high pressures). Bulk hydrogen can also be stored underground for long periods. The geological storage of hydrogen (salt caverns, oil/natural gas reservoirs, and aquifers) has several advantages such as the absence of oxygen and high fluid pressure. Moreover, the technology can store hydrogen over long periods, bridging the gap between summer (with lower demand) and winter (when demand is higher, but production rates have decreased; Zivar, Kumar, and Foroozesh 2021). This technology has been demonstrated in multiple hydrogen storage salt caverns in northern England and the United States (Zivar, Kumar, and Foroozesh 2021).

Compounds containing hydrogen (e.g., ammonia and metal hydrides) are also considered in hydrogen storage for LOHCs. LOHCs require hydrogen to be extracted before further handling after the carriers have been delivered to the destination. Additional infrastructure or processes need to be in place when using these LOHCs as hydrogen carriers. Among the organic hydride family, MCH is envisaged to have the highest potential. This is attributed to its adaptability and flexibility to work alongside the conventional petroleum refining transport and storage infrastructure (Sekine and Higo 2021). However, the MCH dehydrogenation reaction is highly energy-intensive, requiring high operating temperatures. Moreover, a separation system is necessary to purify the outlet gas, adding to the total cost. Membrane reactor technology has been overcome to solve these drawbacks and increase the precision of hydrogen concentration levels (Gas Infrastructure Europe 2021). With membrane reactor technology, the equilibrium of dehydrogenation can be shifted (to the product side) by parting hydrogen from the reaction zone in situ. Under this strategy, higher MCH conversions are obtained at lower temperatures than when using conventional fixed-bed reactors. Thus, it simplifies the separation in further process steps and reduces the overall cost (Gas Infrastructure Europe 2021).

Storing hydrogen using metal hydrates is often the most compact way to keep hydrogen owing to their high density and solid hydrogen containers having higher energy capacity than compressed tanks. This pathway is also the safest method for storing flammable hydrogen gas at lower pressures in small spaces. Metal hydride storage systems operate at 10–40 bar (Von Colbe et al. 2019), 20 times less than typical high-pressure systems.

For ammonia, storage has several advantages over other hydrogen storage media. Ammonia can be kept as a liquid under relatively mild conditions. Two methods are adopted to keep ammonia: (1) increasing pressure and maintaining the ambient temperatures (e.g., 0.99 MPa at 25°C; Aziz, Wijayanta, and Nandiyanto 2020; Valera-Medina et al. 2021), and (2) decreasing the temperature while maintaining ambient pressures (ammonia is cooled to −33.4°C). A significant benefit is that lighter and more cost-efficient tanks can be used for the same volumetric storage density. Moreover, regulations for operations and storage are established. When releasing hydrogen in ammonia, a step-wise decomposition step is followed. The sequence starts with ammonia adsorption on the metal, followed by ammonia dehydrogenation and the recombinative desorption of nitrogen and hydrogen (Aziz, Wijayanta, and Nandiyanto 2020; Valera-Medina et al. 2021). While ammonia handling is well documented, the use of this energy carrier has not been widely adopted for energy harvesting, as the necessary technology is yet to mature (Table 16.3).

Utilization

Hydrogen is a flexible carrier and can be used for many applications, leading to numerous possibilities for medium- and long-term projects in several sectors (Figure 16.2).

Hydrogen utilization for transport

Road transport and mining equipment

Hydrogen provides a way to lower the emissions of road transport and mining equipment by using fuel cell electric vehicles (FCEVs), especially for long-distance use cases and high daily ranges (Hydrogen Council 2021b). In addition,

TABLE 16.3 Hydrogen storage and transport.

Transformation method	*Long-distance transport*		*Short-distance transport*			*Storage*			
	Pipeline	*Tankers*	*Pipeline*	*Trucks*	*Trains*	*Tank*	*Pipeline*	*Can*	*Cavern*
Compression	✓	✓	✓	✓	✓	✓	✓		✓
Liquefaction		✓		✓	✓	✓			
Ammonia	✓	✓	✓	✓	✓	✓	✓		
LOHCs		✓		✓	✓	✓			
Hydrides		✓		✓	✓			✓	
Scale	<2,000 km	<3,000 km	<500 km	<500 km	<1,000 km	*Small/mid**	*Small/mid**	*Small**	*large**

Source: adapted from Energy Transition Institute (n.d.). The checkmarks indicate the applicable transformation method for a specific infrastructure for long- and short-distance transport and storage.

Compression and liquefaction are considered to be physical *transformations,* while ammonia, LOHCs, and hydrides are tagged as *chemical transformations*.

* *Scale is qualitative and relative.*

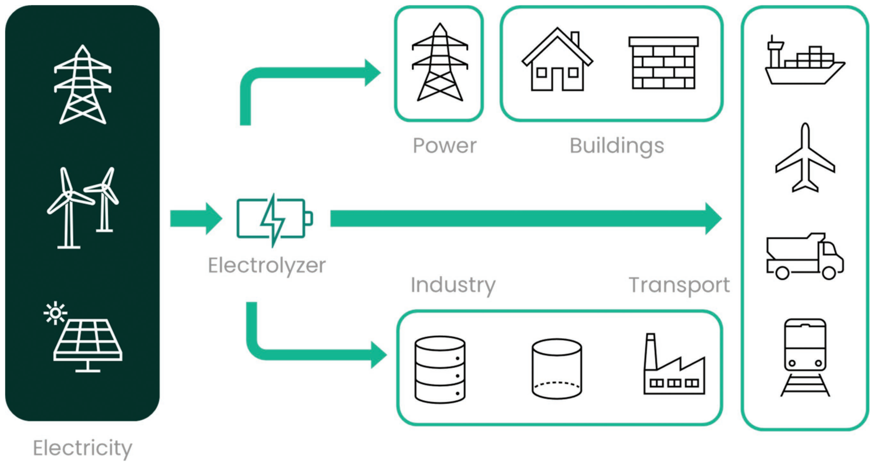


FIGURE 16.2 Hydrogen utilization pathways (nonexhaustive).

Source: Authors adapted from Fuel Cell Store 2020.

FCEVs are the best alternative for the weight-sensitive freight transport used in the pulp and paper, iron, and steel industries. FCEVs can also power larger utility vehicles with long-range requirements and intensive use cycles. When heavy equipment is considered, zero-carbon powertrains are still in development. This application is a clear segment in which fuel cell powertrains or hydrogen combustion engines might be alternatives for lowering overall emissions. A variation of the FCEV is the hydrogen internal combustion engine vehicle, a modified version of the traditional gasoline- or diesel-powered internal combustion engine fed with hydrogen instead.

Shipping

International commercial shipping is a priority sector for lowering emissions (Okonkwo et al. 2021). Owing to the challenges compared with replacing the current fleet, lowering emissions in the shipping industry is envisaged to occur in three stages (Hydrogen Council 2021a):

- In the transitional period, twin-fuel engines running on a combination of conventional heavy fuel oil and alternative fuels will gradually shift toward fuels enabling net-zero emissions.
- In the second phase, internal combustion engine propulsion systems will begin to run on low- or zero-carbon fuels.
- In the final phase, the broader application of alternative propulsion systems such as fuel cell systems that guarantee high fuel efficiency for hydrogen-based fuels will occur.

Container ships, accounting for approximately a quarter of the global fleet emissions, are expected to use green ammonia as the cheapest zero-carbon fuel in the long term (Okonkwo et al. 2021). After the period in which dual-fuel internal combustion engines will predominate, ammonia fuel cells could become the preferred propulsion system given its higher fuel efficiency and expected significant decrease in capital expenditure (Okonkwo et al. 2021).

Liquid hydrogen is expected to be the preferred fuel for ships; however, stringent emission regulations will apply because it eliminates not only CO_2 but also non-CO_2 emissions such as nitrogen oxide and sulfur oxide. Cruise ships are expected to use carbon-neutral methanol and liquid hydrogen as the most viable fuels given their operational nature (e.g., routes, shorter trip durations with frequent stops, and more stringent safety regulations). As for container ships, dual-fuel internal combustion engines will offer a transitional technology for cruise ships until the complete adaptation of methanol internal combustion engines and liquid hydrogen fuel cells (Hydrogen Council 2021b).

Aviation

The aviation sector is considered to be one of the hardest-to-abate sectors (Hydrogen Council 2021b). Emissions reduction options for this sector are limited, with hydrogen one of the best alternatives to cut emissions. Clean liquid hydrogen is a nascent technology used for up-and-coming propulsion systems such as hydrogen-based combustion turbines or fuel cells. However, contrary to other sustainable aviation fuels, using liquid hydrogen requires an overhaul of the existing aviation fuel infrastructure. Based on studies, hydrogen at scale can cost-effectively reduce the emissions of short- and medium-range flights, which account for 70% of global CO_2 equivalent emissions in aviation. However, for flights beyond 10,000 km, hydrogen is not the most cost-competitive emissions reduction option owing to the storage space requirements (Hydrogen Council 2021a, 2021b).

Ammonia utilization

Ammonia represents approximately 45% of the global offtake of hydrogen: 80% of this amount is used as fertilizer feedstock and the rest for industrial chemicals manufacturing (Hydrogen Council 2021b). Ammonia is also recognized as an adequate sustainable fuel in the freight shipping industry. Further, it can serve as a hydrogen transport vector and help lower the emissions of the power generation industry to fire or cofire existing thermal power plants. Envisaged as a carbon-free fuel, research, development, and demonstration have shown that ammonia can be utilized in gas turbines and boilers. For example, Japan is one of the first countries to emphasize ammonia as an adequate fuel in boiler combustion. This technological vision is part of the country's 14-point action plan to reduce greenhouse gas emissions in heavy industries. Several pilot projects using ammonia in coal-fired power plants, gas turbines, and industrial furnace combustion have commenced in partnership with the Japanese Cross-Ministerial Strategic Innovation Promotion Program, with encouraging early results. The learnings from these projects and studies are being translated and targeted for commercialization by the New Energy and Industrial Technology Development Organization. Future R&D and testing are encouraged to overcome the technical bottlenecks and supply chain challenges as well as reduce greenhouse gas emissions across the board (Aziz, Wijayanta, and Nandiyanto 2020; JERA 2020). As a hydrogen carrier, ammonia production is susceptible to hydrogen production costs. In particular, the cost of clean hydrogen production is country/region-specific and primarily driven by energy sources and carbon capture and storage costs. Thus, the attractiveness of clean ammonia compared with gray ammonia from natural gas varies by location. In countries with low-cost feedstocks, such as those in the Middle East, the breakeven cost would be low, allowing a faster and broader expansion of this technology (Hydrogen Council 2021a, 2021b).

Steel and metals production

The steel sector is one of the principal CO_2 emitters, accounting for about 8% of global emissions (Hydrogen Council 2021b). Under pressure from policymakers and society, there is a sharp push to reduce the emissions from steel and metals production. There are two main pathways for reducing emissions in the steel manufacturing process. The first is using a combined blast furnace and basic oxygen furnace (BF-BOF) to manufacture steel from iron ore, with coal as the reductant. The second is using an electric arc furnace (EAF), the main inputs of which are direct reduced iron (DRI) and scraps of steel. While both pathways cause carbon emissions, the conventional BF-BOF process is generally more emissive because coal is one of the precursors. Strategies to reduce emissions on the BF-BOF pathway include reducing production losses, increasing efficiency, and capturing and utilizing carbon. However, most of these strategies do not eliminate emissions and have not yet been demonstrated as economically viable. The DRI-EAF route, on the contrary, can be used to reduce emissions to a greater extent. This pathway requires steelmakers to use renewable power to enable the EAF and add clean hydrogen (or biomass) as the reductant in DRI production (Hydrogen Council 2021a, 2021b; Michaelis, Jackson, and Clift 1998). Through the DRI process, iron production utilizes combinations of natural gas, carbon monoxide, and hydrogen (up to 100%), which can reduce operating costs by controlling gas/hydrogen mixtures depending on their prices. Experts suggest that 30% hydrogen/70% natural gas (by energy) is feasible without significantly altering manufacturing and product quality (Ruth et al. 2020). Several alternatives to reducing iron to enhance process efficiency using hydrogen are in the R&D phase (e.g., flash ironmaking technology; Igogo et al. 2020; National Renewable Energy Laboratory 1998, n.d.; Office of Industrial Technologies 1998).

Synthetic hydrocarbons

In addition to the variety of applications in which hydrogen can be used as the primary fuel, hydrogen can also produce various synthetic hydrocarbons to enter and compete in the chemical and fuel sector. These synthetic hydrocarbons are alternatives to liquid fuels (e.g., for long-haul trucks) and industrial feedstocks in the (petro)chemical sector (e.g., methanol; National Renewable Energy Laboratory n.d.). When using hydrogen for carbon utilization in synthetic fuels, it is vital to understand the full lifecycle assessment of the process to assess its impact on energy resources and the climate accurately (Van der Giesen, Kleijn, and Kramer 2014).

Blending with natural gas

Natural gas/hydrogen blending integrates concentrations of hydrogen into existing natural gas pipelines to reduce methane intensity (Fuel Cell & Hydrogen Energy Association n.d.). Injecting hydrogen into pipelines is a hydrogen strategy used globally. From an environmental standpoint, blending hydrogen with natural gas can significantly reduce greenhouse gas emissions if low-carbon energy technology (with carbon capture technologies) and renewables enable the hydrogen production process. On a volumetric basis, hydrogen has a lower energy density than natural gas; therefore, end-users of this blend require a higher volume to achieve the same heating value as 100% natural gas. Moreover, studies show that blending hydrogen up to 20% (by volume) into the gas grid requires minimal alterations to infrastructure (grid) or home equipment and appliances (IEA 2019).

Power generation

With wind and solar (so-called variable renewable energy technologies) having their output as a function of resource accessibility, which also depends on the climatic patterns of a location, they are often considered to be a nondispatchable electricity generation source compared with traditional coal- and gas-fired power plants (Argus Media 2021). Hydrogen is under consideration as a future energy storage carrier. As electricity prices are expected to be relatively low, this will make hydrogen production using electrolysis economically viable, with the final product stored in tanks, salt caverns underground, and in depleted or abandoned oil and gas infrastructure. The stored hydrogen can then be blended with natural gas to generate power and burnt directly in power plants depending on various factors such as availability, electricity, and commodity prices. Additionally, the commercialization of solid oxide fuel cells would efficiently use the hydrogen stored for power generation (H2 Industries n.d.).

Most combined-cycle gas turbines can accommodate natural gas/hydrogen blends. The limit on the hydrogen in the fuel mix varies depending on the turbine model. Novel turbine designs and materials will help address the challenges of using hydrogen compared with natural gas (e.g., higher flame temperatures, higher laminar flame speed, and lower autoignition delay; H2 Industries n.d.). Turbomachinery and process solutions providers are developing solutions for power plant infrastructure and systems that run 100% hydrogen (Feder 2021).

Current examples of utilization and prospects

Port of Duqm for exporting hydrogen

Feasibility studies of a large-scale green hydrogen project in Oman are ongoing. The HYPORT Duqm Project, an exclusive partnership between the Belgian engineering firm DEME and OQ Alternative Energy, is aiming to build a 250–500-MW electrolyzer facility for producing green hydrogen or hydrogen derivatives such as ammonia (DEME Group 2020). The Port of Duqm is in an economically strategic zone because of its high winds and solar energy production capacity. The project will be connected to the port by the newly constructed export terminal, storage infrastructure, and liquid jetties (Uniper 2021). The area is also home to a large refinery and developing industrial zone, which is aiming to transform into a renewable energy hub, thereby establishing Oman as a key player in the green hydrogen value chain. The project will also support the emissions-reduction efforts of the local chemical industry and serve customers overseas (CFE n.d.; DEME Group 2020). The projected investment is $500 million and commercial operations are expected to start in 2024.

Blue hydrogen and ammonia supply chains

A year-long collaborative feasibility study between ENEOS and Saudi Aramco is underway to evaluate the use of hydrocarbons for producing blue hydrogen and blue ammonia in Saudi Arabia as well as the options for capturing the carbon resulting from this process. This study also intends to assess the viability of various chemical carriers (e.g., ammonia and MCH) for transporting hydrogen, including an in-depth analysis of how to deliver hydrogen to Japanese markets (F&L Asia 2021). After the feasibility study, ENEOS intends to import hydrogen and related products to generate power at its refineries and in local companies.

25 GW wind/solar complex in Oman

Ambitious plans have been laid out by a consortium involving one of the world's largest green hydrogen developers, InterContinental Energy, and Oman's national energy company OQ to construct a 25-GW wind/solar complex in Oman (Renewables Now 2021). At full capacity, it will produce 1.75 million tons of green hydrogen per year. The planned project is near the coast for seawater intake and electrolysis and could achieve 9.9 million tons of green ammonia annually

(Wind Power Monthly 2021). The project is expected to be operated entirely on renewable wind (16 GW) and solar (10 GW) energy. Initial offtake agreements can be expected around 2024, with the final investment decision made around the same time. The project is envisaged to reach full capacity by 2038 (one-third of capacity by 2032; Renewables Now 2021). The total investment for this project is approximately $14 billion.

Solar-powered green hydrogen plant in Dubai

With support from the Dubai Electricity and Water Authority and Expo 2020 Dubai, Siemens Energy has developed and built a solar-powered green hydrogen plant in the region. The facility is housed at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai as part of the UAE's plan to increase clean energy use in the country from 25% of the energy mix to 50% by 2050 (Hydrogen Council 2021b). The project is located at the Outdoor Testing Facility of the Dubai Electricity and Water Authority Research and Development Center, covering an area of 10,000 m^2. The green hydrogen production facility is enabled by proton exchange membrane electrolysis technology.

Neom Green Hydrogen Company, Saudi Arabia

This hydrogen-based ammonia production facility powered by renewables is planned in Neom in Saudi Arabia. Dubbed one of the world's largest green hydrogen plants, the investment is estimated to be $5 billion. The NEOM Green Hydrogen Company (NGHC) will produce 650 tons of green hydrogen every day, enabled by a 4-GW electrolyzer powered by renewables, sufficient to run 20,000 hydrogen-fueled buses. The NGHC comprises a green ammonia plant with a capacity of 1.2 million tons per year, with production expected to start in 2025 (Hydrogen Council 2021b).

Case study: Baker Hughes

Baker Hughes, an energy technology company, is organized into four product companies (oilfield services, oilfield equipment, turbomachinery and process solutions, and digital solutions). It covers a diverse equipment portfolio and service capabilities catering to the broad energy and industrial value chains with a global scope. As part of its acceleration into the energy transition space, the company offers a wide range of solutions in the hydrogen arena. More than 70 projects globally use the company's frame and aero turbines for various fuel mixtures of high hydrogen content. Furthermore, Baker Hughes has more than 5,000 compressors installed globally, with 2,000 of these being hydrogen compressors catering to all forms of hydrogen technologies.

Hydrogen-blend turbine for gas pipelines

In 2020, the company tested the NovaLT 12, the world's first "hybrid turbine," using up to 10% hydrogen blend at the compressor station of Snam in Istrana, Italy. Snam is one of the largest gas transmission and storage operators in Europe. The Baker Hughes NovaLT family is a collection of the industry's first high-performance gas turbines designed for hydrogen and other lower carbon fuels (can burn fuel blends from 5% to 100% hydrogen; Baker Hughes 2020). The system was developed by employing computational methods (fluid dynamics, thermo-acoustic assessments), additive manufacturing, and combustion tests (lab-to-pilot scale tests). The NovaLT™ has been designed to provide operational flexibility as well as lower maintenance intervals, costs, and emissions as low as single-digit ppm nitrogen oxide. Tests show that the installation of this system will allow Snam to handle 7 billion m^3 of hydrogen per year and reduce up to 5 million tons of CO_2 per year during operations (Baker Hughes 2020).

Hydrogen compression in a downstream refining facility

Thai Oil's Clean Fuel Project is one of the biggest energy projects in Thailand, as the country pivots to become one of Southeast Asia's energy hubs (NS Energy n.d.b). The project aligns with current market conditions and regulations, such as reducing fuel oil use and implementing Euro 5 standards for gasoline and diesel (Oil & Gas Journal 2020). In 2018, the Clean Fuel Project decided to expand the 275,000 barrels/day Sriracha Oil Refinery (operating since 1964) to 400,000 barrels/day. Moreover, the installed units will be more environmentally friendly from construction to operation (Baker Hughes 2021a). Baker Hughes will supply four API 618 reciprocating compressors to cover all the units in the expanded refining facility. The company has already supplied four identical units to cover all facility services. Each unit includes relative auxiliary cooling and lubrication systems and is driven by a 20-MW electric motor. With a footprint of 11 × 15 m and weighing more than 330 tons, each unit has a capacity of 9,150 m^3/h of hydrogen. The reciprocating compressor has eight cylinders, considered the largest installed for a downstream refining facility (Baker Hughes 2021a).

Digital solutions in hydrogen technologies

Baker Hughes' sensor solutions can be used to monitor processes across the value chain. Integrated with the company's energy equipment offering, Baker Hughes develops sensors and leak detection instruments and flow and metering applications. Panametrics, a Baker Hughes business, focuses on developing measurement technologies such as vortex and ultrasonic flow meters, flare management solutions, and gas and moisture analyzers. These sensor technologies can be deployed in several processes in the hydrogen value chain to monitor process parameters such as hydrogen (im)purity, oxygen detection, and moisture analysis (Baker Hughes n.d.). For example, one of the technologies offered combines a technologically advanced aluminum oxide moisture sensor with advanced analytics (HygroPro) to detect moisture in hydrogen production applications (e.g., fuel cells).

Moreover, inline systems (MMY31) or an integral flow cell (MMY30) are also available for filtration and flow regulation. Further, Baker Hughes' Panametrics offers a thermal conductivity analyzer (XMTC) suitable for hydrogen production systems and equipped with solvent-resistant cells. Oxygen sensors are also offered, such as the company's oxy.IQ sensor, which has several measuring ranges for analyzing oxygen (Baker Hughes n.d.). Baker Hughes has inspection solutions capabilities in the Digital Solutions segment, such as Waygate Technologies and Process and Pipeline Services. These inspection capabilities apply to equipment structural integrity evaluation, which can be extended for monitoring hydrogen embrittlement and detecting metal loss and cracking in hydrogen pipelines. Asset performance management, controls for integrated compressor and turbine control, and cybersecurity are all enabled by technologies from Bently Nevada and Nexus Controls.

Baker Hughes and external partnerships

In 2021, Baker Hughes and Bloom Energy announced a collaboration to explore integrated technologies for the energy and industrial sectors. With the solid oxide fuel cell technology from Bloom Energy and turbomachinery technology and process solutions from Baker Hughes, the partnership envisages developing economical technologies for clean energy production, heat integration (e.g., waste heat recovery), and standalone (i.e., grid-independent) power (Baker Hughes 2021b). Baker Hughes and Bloom Energy will combine solid oxide electrolyzer cells and compression technology to allow hydrogen production, compression, and transport. Process engineering optimization (e.g., using waste heat for steam generation) will be further studied to optimize process and cost efficiencies. Furthermore, the companies will assess and implement hydrogen blending into natural gas pipelines and on-site hydrogen production for various industrial sectors (e.g., steel refining, and cement). Baker Hughes and Bloom Energy will also extend this partnership to carbon capture technologies, emissions management, digital technology solutions, and additive manufacturing (Baker Hughes 2021b).

In mid-2021, Baker Hughes announced a strategic collaboration with Air Products, a world leader in industrial gases and project development, to develop efficient and cost-effective hydrogen compression and gas turbine technologies. These projects will include the net-zero hydrogen energy complex in Edmonton, Alberta, and Canada and advanced compression technology for Saudi Arabia's Neom hydrogen project (Air Products 2021). Later, in 2021, Baker Hughes announced its investment in Ekona Power to develop and commercialize a methane pyrolysis technology to produce cleaner and lower cost turquoise hydrogen. Methane pyrolysis technology yields hydrogen with lower emissions and is suitable for petrochemical sites, refineries, ammonia/chemical plants, natural gas transmission, and distribution companies. Ekona Power's methane pyrolysis technology employs high-speed gas dynamics and combustion, separating the feedstock (methane) and products (hydrogen and solid carbon). Therefore, the process can be integrated with standard natural gas and hydrogen equipment, thereby simplifying the incorporation of industrial processes. With this partnership, industrial projects—both modular and scalable solutions for hydrogen pilots and natural gas projects—are being targeted (Baker Hughes 2021c).

Baker Hughes has over 80 years of presence in the Kingdom of Saudi Arabia and the wider region through its collaboration with the national oil company, Saudi Aramco. The company also has strong alliances with key research institutes in the country, such as the King Abdullah University of Science and Technology and the King Abdullah Petroleum Studies and Research Center. The Dhahran Technology Center is a dedicated Baker Hughes research institute focusing on energy solutions, with a heavy emphasis on digital. The Center is an active contributor to the Kingdom's sphere of innovation. This R&D facility focuses on digital transformation through artificial intelligence, Industry 4.0, design and manufacturing, and sustainability. The Center is home to Saudi Arabia's first 3D metal printer and it collaborates with regional and international technology networks, energy providers, and academic and research institutions.

Conclusion

The scalable production and adoption of hydrogen are imperative to achieve net-zero carbon emissions. However, as outlined in this chapter, technological barriers must be overcome across the value chain, including production, transport, storage, and utilization. Engineering challenges include producing advanced materials for handling hydrogen, developing sensors, ensuring cost-effective integration into existing and newly built systems, and calculating across-the-board lifecycle emissions accurately. Therefore, strong collaboration between academia and energy technology companies is critical.

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17

SAUDI ARABIA AND THE HYDROGEN ECONOMY

Blue and green hydrogen value chain

Michelle Schoonover, Mustafa Alkhabbaz and Mark D'Agostini

Introduction

Renewable energy is a clear solution to reduce global carbon dioxide (CO_2) emissions; however, renewable energy in the form of wind and solar power alone cannot reduce CO_2 emissions in all industries. This is where hydrogen comes in. Hydrogen is considered an energy carrier. It can be made from several different primary energy sources, including fossil fuels and renewable energy. It can then be used in energy-intensive industries where direct use of renewable energy to reduce CO_2 emissions is not always feasible or possible (e.g., cement and steel production). Hydrogen can also be used as a fuel for markets with multiple end-use points where post-combustion carbon capture is not practical (e.g., in mobility and in building heating (blended with natural gas)). In addition, hydrogen can enable long-duration storage of renewable energy, to mitigate curtailment in grids with high penetrations of renewables. The sectors that hydrogen can help decarbonize currently make up 65% of today's global greenhouse gas (GHG) emissions.[1]

Not all hydrogen is equal from a CO_2 emissions perspective. If hydrogen is produced using a nonrenewable energy source and the CO_2 by-product is fully emitted to the atmosphere, it is considered gray hydrogen. The carbon intensity[1] of gray hydrogen from a steam methane reformer (SMR) includes both direct emissions from the plant operation, indirect emissions from the energy consumed, and upstream emissions from natural gas production and transportation. The value depends on a number of factors, including the efficiency of the SMR and the source of natural gas and electricity. As one example, a value of around 80 kg CO2e/GJ H2 has been quoted in literature.[2] If hydrogen is produced using a nonrenewable energy source and the CO_2 is captured and sequestered or utilized, it is considered blue hydrogen. Hydrogen recovered from waste gases may also be considered blue hydrogen, as

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this is a low-carbon method of producing hydrogen. The carbon intensity of blue hydrogen can vary significantly depending on the technology used for the hydrogen production and the amount of CO_2 captured. The carbon intensity of blue hydrogen can be about 85% lower than that of gray hydrogen.[2] Hydrogen produced from renewable energy (e.g., solar, wind, hydro, biogas/biomass) is considered green hydrogen. The process of green hydrogen production from water electrolysis using renewable energy does not itself produce any CO_2 emissions. The carbon intensity associated with green hydrogen via water electrolysis is mainly from the manufacturing of the components used in the generation of renewable power (wind, solar, hydro).[2] The carbon intensity can be much less than 10 kg CO_2e/GJ H_2 depending on how and where the components are manufactured.[2] Green hydrogen produced from biomass resources (e.g., biogas) with carbon capture and sequestration has a negative carbon footprint over its life cycle, since the biomass represents sequestered carbon, and the carbon dioxide released in hydrogen production is ultimately sequestered as well.

Blue hydrogen is expected to bridge the gap in the transition from gray to green hydrogen. Green hydrogen is at a significant cost disadvantage today. Access to low-cost electricity, electrolyzer efficiency improvements, and reductions in capital cost (e.g., through R&D and economies of scale) are all necessary to make green hydrogen cost competitive. There are also regional challenges to overcome with generating the renewable power necessary for electrolyzers to make green hydrogen, such as land area and grid infrastructure. Blue hydrogen technology is based on traditional reforming or gasification technology for hydrogen production and has been demonstrated at scale; however, the success of blue hydrogen is constrained by two factors: somewhere to sequester or utilize the captured CO_2 and a business case that justifies the cost of CO_2 capture. Government policies and regulations that incentivize blue hydrogen and decarbonization projects will be the key driver for large-scale project developments in Saudi Arabia and other parts of the world.

Industrial gas companies like Air Products are taking a lead role in blue and green hydrogen offerings. Air Products has been operating two blue hydrogen SMRs in Port Arthur, TX, USA since 2013. Combined, they capture about 1 million tons/year of CO_2, which is then used in enhanced oil recovery (EOR).[3] In 2020, Air Products, in a joint venture with ACWA Power and NEOM, announced the NEOM Green Hydrogen Project, a multibillion-dollar world-scale green hydrogen project in Saudi Arabia. This will be one of the world's largest green ammonia projects to sustainably supply carbon-free green hydrogen for transportation globally while abating an estimated three million tons of CO_2 per year.[4]

In 2020, Aramco in collaboration with SABIC and Japan's Institute of Energy Economics demonstrated a low-carbon product value chain by producing and shipping 40 tons of blue ammonia from Saudi Arabia to Japan to be used for low-carbon power generation. The produced CO_2 was utilized for both methanol production at a SABIC facility and EOR at Aramco's Uthmaniyah field.[5] This was a key step towards demonstrating the circular carbon economy framework which was promoted by Saudi Arabia and endorsed by the G20 leaders during the G20 summit presided by Saudi Arabia in 2020. In addition, Saudi Arabia announced the Saudi Green Initiative (SGI) that aims to reduce carbon emissions by more than 130 million tons.[6] Accelerating large-scale green and blue hydrogen projects can play a critical role in achieving the SGI targets in a timely manner and can position Saudi Arabia as a global leader in decarbonization efforts.

When it comes to the energy transition, hydrogen can be a real game changer – when produced in a low-carbon way, it can significantly reduce CO_2 emissions far beyond the electricity sector and play a key role in decarbonizing many industries making them less dependent on unabated fossil fuels. Making the transition to hydrogen as a primary energy source is not going to happen overnight. The world will still be dependent on fossil fuels for many years to come. It is for this reason that blue hydrogen will play a critical role in helping us reduce CO_2 emissions today while projects like NEOM are introducing green hydrogen to the world at a large scale.

Strategy

Air Products is the world's leading producer of hydrogen. Hydrogen is expected to make up a larger portion of Air Products' portfolio by 2035. Being an industry leader, Air Products is unlocking a cutting-edge hydrogen economy through its strategic investments in mega projects like NEOM Green Hydrogen that will play a major role in helping Saudi Arabia reach its plans to reduce CO_2 emissions and position the country as a major player in exporting clean hydrogen to the world.

The versatility of hydrogen in being able to decarbonize a broad range of sectors is leading to an increase in the number of hydrogen end-use applications, such as steel production and high-temperature heating.[7] As a result, there is a need for a variety of solutions across the supply chain that will meet the customer requirements driven by each end-use application. For example, the tight purity specifications for fuel cell grade hydrogen will require a different purification technology than hydrogen that will be blended with natural gas for use as a lower carbon fuel. In addition, the increased need for distributed supply, particularly for fueling stations, is driving innovations around how to best transport and store hydrogen. Opportunities for technology development exist throughout the hydrogen supply chain, including blue and green hydrogen generation, transportation, storage, and end use.

Air Products is seeing a shift from the traditional SMR-based "gray" hydrogen production to lower carbon "blue" and renewables-based "green" hydrogen production. The most common way of producing hydrogen today is through steam methane reforming. SMRs produce hydrogen in a process where a gaseous hydrocarbon feedstock is mixed with steam and passed over catalyst-filled tubes in a reformer that is heated with a hydrocarbon fuel. This is the most cost-effective

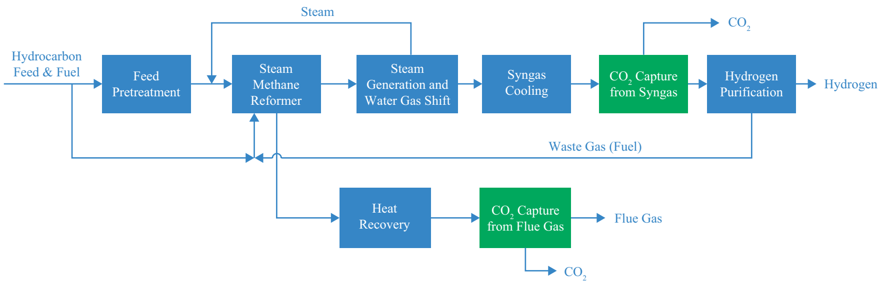

FIGURE 17.1 Blue hydrogen SMR block flow diagram.

means of making hydrogen today; however, all CO_2 from this process is typically emitted to the atmosphere. As a first step in reducing CO_2 emissions from the SMR process, the CO_2 generated as a by-product of the process and/or from combustion in the furnace must be captured and either sequestered or used in another process (e.g., EOR). This changes the classification of the hydrogen from gray to blue. Carbon capture technologies can be retrofitted onto existing SMRs or included in the design of new SMRs.

SMRs generate CO_2 in two places – on the process side of the reformer and on the furnace side of the reformer, as illustrated in Figure 17.1. The CO_2 on the process side is at higher pressure and is therefore more economical to capture. The CO_2 on the furnace side requires more energy to capture because it is contained in a low-pressure flue gas stream that is typically vented to atmosphere. Therefore, without significant changes to the process, it is often economically practical to capture ~50%–60% of the CO_2 from the process side of an SMR plant. Air Products has demonstrated this with its CO_2 capture project in Port Arthur, TX, USA, which utilizes vacuum swing adsorption (VSA) technology to capture and purify ~1 million tons/year of CO_2 from two SMRs for use in EOR.

Depending on the value given to captured CO_2 through tax credits, carbon pricing, market demand, or other incentives, it may be more advantageous to turn to autothermal reforming (ATR) or partial oxidation (POX) technology for blue hydrogen generation, where a greater amount of CO_2 can be captured economically particularly for larger hydrogen plants (> 150,000 Nm3/hr). These processes also use a hydrocarbon feedstock mixed with steam to produce hydrogen; however, they also require an oxygen stream, which today typically results in a higher cost relative to SMRs. The advantage of an ATR or POX process is that the heat generation for the reaction is accomplished within the reactor itself thus minimizing or eliminating a vented flue gas stream. This makes it possible to economically capture as much as 95% or more of the CO_2 generated by these processes. One of the key differences between ATR and POX reactors is that POX reactors have no catalyst. They can operate on a variety of feedstocks with no or minimal feed pretreatment. They can also operate at high pressure (up to 87 bar) thus minimizing hydrogen compression costs. The ATR or POX process is illustrated in Figure 17.2.

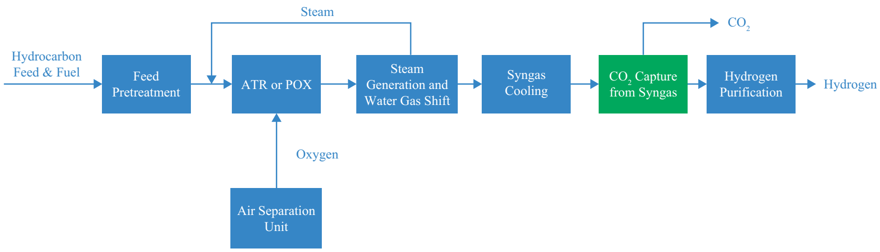

FIGURE 17.2 Blue hydrogen ATR or POX block flow diagram.

For smaller hydrogen plants, where the cost of oxygen production through an air separation unit makes it expensive to use an ATR or POX cycle, additional modifications can be made to an SMR to substantially reduce CO_2 emissions. Air Products has a patented process that includes two stages of water-gas shift, CO_2 capture from the syngas, recycle of waste gas from the hydrogen purification unit, and hydrogen as fuel in the reformer. In the example provided in the patent, the process cycle reduces the CO_2 in the vented flue gas stream by >95%.

For blue hydrogen, it is important to find cost-effective ways to capture the maximum amount of CO_2 from traditional reformer-based hydrogen production processes but, even more important, is finding appreciable sinks to sequester or utilize this captured CO_2. CO_2 sequestration and EOR have been demonstrated at a large scale, for example, at Aramco's Uthmaniyah demonstration project in Saudi Arabia, and present a proven option for disposing of large quantities of CO_2. Conversion of CO_2 into valuable products is more challenging, particularly at large scale. CO_2 is very stable and therefore requires an energy-intensive process to convert it into valuable products. For this reason, it is important to ensure that any CO_2 utilization pathways yield a reduction in CO_2 on a life cycle basis. Many organizations are developing new technologies to improve the technical feasibility, cost competitiveness, and scale of CO_2 conversion options. Figure 17.3 shows carbon capture, utilization, and storage (CCUS) pathways for KSA industries. More than 20 pathways were analyzed including CO_2 capture from main emitting industries resulting in low carbon products, CO_2 conversion, and CO_2 storage pathways.

To maximize CO_2 emission reduction, green hydrogen must be produced using renewable energy (typically, electrolysis from renewable power or biomass/biogas processing) and transported/supplied in a carbon-neutral manner. The primary challenge with the deployment of larger scale electrolysis plants is capital and operating cost. R&D and economies of scale are both needed to lower capital costs and improve electrolyzer efficiency. Low-cost energy available for long durations throughout the year is needed to achieve low-operating cost. Large-scale deployment of electrolyzers will require companies and governments to make meaningful investments in this area. Electrolyzers powered by intermittent renewable power will additionally need to be integrated with balance-of-plant and downstream

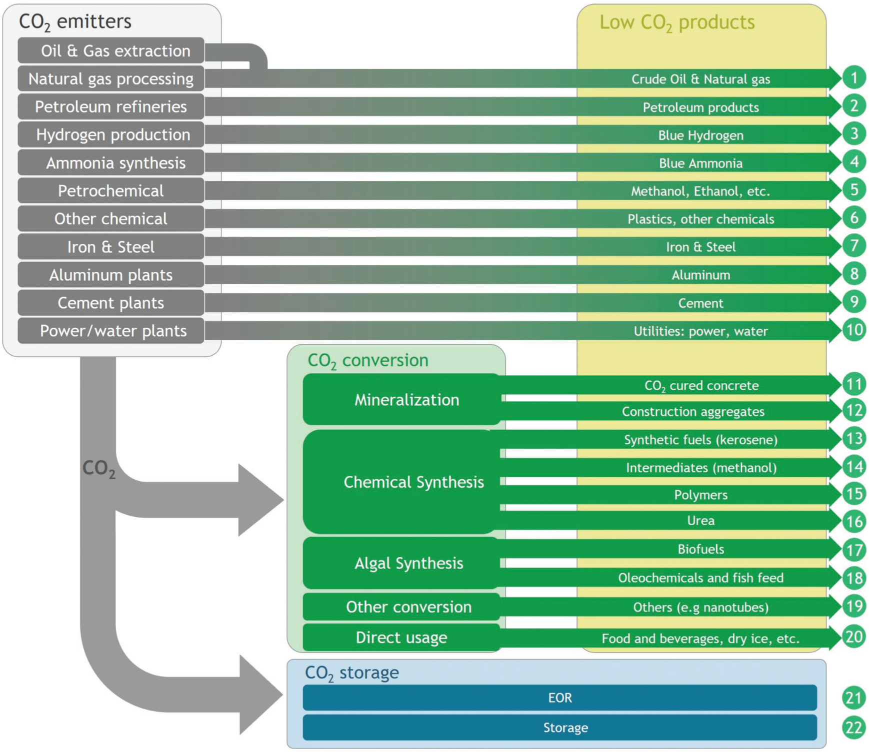

FIGURE 17.3 CCUS pathways across industry emitters, CO_2 conversion, and CO_2 storage dimensions. Credit: Air Products – BCG analysis: CCUS strategy for KSA.

processes that allow for flexible operation such as compressors and storage. Currently, carbon capture and storage (CCS)-equipped coal gasification and Blue SMR/ATR/POX pathways are lower cost than electrolysis from renewables; these are a viable solution while industrial-scale green hydrogen production continues to ramp up, particularly in regions of the world like Saudi Arabia where plentiful sun and wind make production cost-effective.

Government policies and regulations for hydrogen and decarbonization projects will be the key driver for large-scale projects. They will play a critical role in reducing barriers through policy and regulation as well as providing CCUS infrastructure. Together with other considerations, governments will have to decide on the relevance of blue hydrogen projects in their regions based on the availability of suitable geological storage locations either within national boundaries or accessible locations nearby. In order to benefit from blue hydrogen, governments should establish national CCUS strategies with clear targets and commitments, including consistent CO_2 capture requirements. In addition, a clearly defined CCUS legal and regulatory framework can enable and accelerate the development of large-scale hydrogen and CCUS projects. Developing key transport and storage infrastructure in addition to CCUS hubs that are in close proximity to the large CO_2 emitting areas, for example, industrial cities, should be a priority due to the role it can play in reducing the barriers to CCUS project implementation. Furthermore, assessment of CO_2 storage potential, suitable locations close to CCUS hubs, and clear CO_2 storage regulations will be key as sequestration is expected to be the main sink for the large amounts of captured CO_2.

In addition to policy support in Saudi Arabia, financial enablers and development of capabilities are required for deployment of large-scale decarbonization projects. An evaluation of the KSA-relevant financial enablers is required. These enablers could be a combination of:

- Subsidies for GHG emissions reduction – government can enable CCUS investment by providing a subsidy for net GHG reduction.
- Government grants for CCUS projects – government contributes to setting up CCUS facilities by covering part or whole of project expenditure.
- Government direct investment in CCUS project – sovereign wealth fund or state-owned company partners with private players to set up CCUS projects using equity investments.
- Government-owned entity for CO_2 transport and storage – state or sovereign wealth fund-owned company owns and operates CO_2 transport and storage infrastructure that allows private players to use for low fees.
- Government-regulated entity for CO_2 transport and storage – infrastructure built by a private company that allows other users access for CO_2 transport and storage under a government-regulated model.
- Government incentives for lower carbon intensity transportation and other hydrogen demand.
- Research and Development (R&D)–related policies that encourage and kick-start projects that aim to develop technologies with advanced technology readiness levels (TRLs) and result in commercial scale developments.

Applications of low-carbon hydrogen

Utilization of blue and green hydrogen is most likely to benefit end-use market segments such as heavy-duty transportation and those that will not be able to directly electrify with renewable power, such as cement and steel. As more blue/green hydrogen sources are brought on-stream, it is likely that the electric power generation industry will be an early adopter of hydrogen as they start to decarbonize the power grid. Power generation companies have an incentive to embrace hydrogen because they are likely to be producers as well as users, since the use of off-peak power can be conveniently directed to an electrolyzer for hydrogen production. Steel producers are also seriously considering switching to hydrogen combustion for certain unit operations where the higher water vapor content is not likely to negatively affect product quality. Refineries are clearly interested and have an advantage over most industries since they have hands-on experience with hydrogen combustion in many of their furnace processes. There's activity in many smaller industries as well. For example, customers in the Glass, Metals Processing, and Packaged Boiler industries have shown an interest in hydrogen combustion demonstrations, as they wish to better understand the impact of hydrogen on their process efficiency/cost and product quality.

Hydrogen combustion

Prior to converting a combustion process from a hydrocarbon fuel to hydrogen, it is essential to understand how differences in fuel properties may affect the process characteristics. As is evident from Table 17.1 which highlights key combustion properties for natural gas/methane and hydrogen, these differences can be substantial in magnitude. While a proper assessment of conversion to hydrogen in a specific combustion application should indeed address differences in each of these properties and perhaps others; for introductory purposes, brief remarks are offered on the following subset:

Laminar flame speed

Laminar flame speed, sometimes referred to as laminar burning velocity, is related to the reactivity of the fuel–oxidizer mixture. The higher the flame speed, the more reactive the mixture. A practical consequence of the order of magnitude increase in laminar flame speed from natural gas to hydrogen illustrated in Table 17.1 is a higher propensity for premixed air-hydrogen burners to suffer from flashback, which poses safety and equipment life concerns. A further effect of the higher flame speed is the tendency to generate a shorter flame with a higher proportion of heat release closer to the burner nozzle. Consideration should thus be given to changes in temperature distribution and heat transfer within the furnace space with particular attention to heat flux on or near the burner firing wall, for example, to prevent exceeding of the critical heat flux in water-tube boilers or degradation of refractories.

TABLE 17.1 Combustion property comparison between natural gas and hydrogen air-fuel basis

Property	*Units*	*Natural gas/Methane*	*Hydrogen*
Heating Value	Btu/scf	900–1,100	325
Ignition Energy in Air	mJ	0.29	0.02
Wobbe Index	kcal/Nm^3	11,597	9714
Req'd Oxygen	lb O_2/MMBtu fuel	164	128
Flammability Range	Mol%	5–15	4–75
Laminar Flame Speed	cm/sec	35	270
Flame Temperature	Deg C	1875	2045
H_2O Conc. of Flue Gas	Vol%	>15	>30

Volumetric heating value

The volumetric heating value of hydrogen is nominally a third of that for natural gas. A practical concern is that, for a given burner firing rate, the burner fuel nozzle velocity will be roughly 3 times higher for hydrogen. The higher velocity will in turn drive reactant mixing rates higher with the further tendency to shorten the flame and increase turbulence in the combustion space. Because these changes are often undesirable, the likelihood is that operation of incumbent burners will be limited in the permissible degree of hydrogen blending into natural gas.

Stoichiometric combustion air flow rate

The mass of combustion air required for hydrogen combustion per unit of energy released is nominally 20% lower than for air-natural gas combustion. Depending on the air/fuel ratio employed in the combustion process, flue gas mass flow rates will also be much lower for air-hydrogen combustion. In steam boilers, for example, where a precise balance is generally required between radiative and convective heat transfer, the reduction in flue gas flow rate will lead to lower rates of convective heat transfer. When coupled with the anticipated lower emissivity of hydrogen flames and its effect on radiant heat transfer, this could present challenges in maintaining steam production during hydrogen refueling for boiler applications.

Flue gas moisture content

The products of hydrogen combustion contain approximately twice the volumetric concentration of water vapor compared to natural gas combustion. The effect of the added water vapor should be assessed with respect to structural steel corrosion, refractory degradation, and product quality (heating/melting furnaces).

It is hopefully clear from this brief overview that diligence is needed on the part of the end user prior to converting a process from a hydrocarbon fuel to hydrogen. Many useful primary assessment tools such as computational fluid dynamic and process modeling are nevertheless readily available to predict areas of greatest concern, while burner and process testing should be considered for final risk mitigation.

Hydrogen for mobility

In addition to combustion, another key area for blue and green hydrogen utilization is the mobility sector. In June 2019, Air Products and Saudi Aramco inaugurated the first hydrogen fueling station in Saudi Arabia at Air Products' Technology Center in Dhahran Techno Valley Science Park. GHG emissions from the mobility sector make up about 17% of the global GHG emissions today.[1] It is also estimated that

29% of the global hydrogen produced in 2050 will be for the mobility sector.[1] Battery electric vehicles (BEV) are the main competitor of hydrogen in this sector and may prove to be a better option for the light-duty vehicle market.[8] Hydrogen fuel cell electric vehicles are expected to have advantages over BEV for heavy-duty vehicles, such as trucks, buses, and trains, where the weight of the batteries becomes excessive and the battery charging time is long.[9] It is expected that the demand for hydrogen for mobility will continue to grow[1] and it will be important that the fueling station infrastructure is in place to allow for this.

Industrial synergies

Synergies between different industries should be encouraged to build the hydrogen economy. For example, renewable energy providers and green hydrogen producers should be working together to determine how to best integrate their systems, especially considering the challenge that comes with intermittent supply of renewable energy. This may also open the door to a synergy between renewable energy providers and conventional power companies to establish the necessary infrastructure to support future green hydrogen projects. There are also potential synergies between natural gas pipelines and hydrogen suppliers/users. One option is for hydrogen to be blended with natural gas as a means of decarbonizing fuel. Many grid network operators think a 20% hydrogen blend is achievable at this early phase.[10,11] This enables decarbonization of a wide range of natural gas users, including both residential and industrial users. The existing natural gas distribution infrastructure can also provide a means of transporting of hydrogen. Hydrogen can be added to the pipeline at one location and extracted from the pipeline and separated from the natural gas at various use points. Refineries, chemical companies, and energy companies that are developing plans for additional hydrogen capacity for decarbonization can work with industrial gas suppliers who can provide on-purpose blue or green hydrogen but can also make use of waste gas streams from these processes to provide further decarbonization.

Research

There is research taking place throughout the entire blue and green hydrogen supply chain. Research in the following areas will help develop blue and green hydrogen technologies.

Blue Hydrogen:

- Reducing the cost of high-ratio carbon capture in blue hydrogen production
- Development of separation technologies to efficiently recover and purify hydrogen and CO_2
- Development of technologies for valorizing captured CO_2

Green Hydrogen:

- Increasing operating current densities and improving efficiencies of electrolyzers
- Standardization and automation of manufacturing of electrolyzers
- Lowering component-related costs
- Improving flexible operational capabilities
- Minimizing electrolysis cell performance degradation over time

General:

- Development of various options to increase transportability and storage of hydrogen
- Utilization of biomass/biogas in hydrogen production

Technical and academic institutions are studying many options for producing low-carbon hydrogen, including pyrolysis, waste and renewables to hydrogen, and others.

TRLs can be used to illustrate the maturity of a given technology along a scale of 1 (Basic Research) to 9 (System Proven for Full Commercial Deployment). Based on Air Products' internal assessments, blue hydrogen pathways currently have a TRL between 7 and 9. For instance, the TRL of SMR+CCS is 9, whilst ATR/POX+CCS is 8, and coal gasification+CCS is ~7–8. Electrolyzer technology for green hydrogen is also available today but some water electrolysis technologies are more advanced than others. Alkaline and proton exchange membrane electrolyzers are ready for commercial deployment (TRL ~8–9), solid oxide electrolyzers are in the demonstration pipeline (TRL ~5–6), and anion exchange membrane electrolyzers are in the development phase (TRL ~2–3).[12]

Government incentives will be required to encourage technology development at all TRL levels. For technologies at higher TRL levels, encouraging projects that demonstrate scalability of new technology will be very important, particularly in the area of green hydrogen, where electrolysis is a proven technology, but will need to be scaled to much larger sizes to meet future demand. For those technologies that are at a lower TRL level, a country or region-specific hydrogen strategy and roadmap is helpful for defining expectations and can focus new technology development to meet the country's or region's goals and targets. Currently, blue and green projects require a sizeable amount of financial support and/or recognition of the value of lower-carbon energy to make a viable business case. In order to reduce the amount of government support needed in the long run, R&D-related policies should encourage and kick-start projects that aim to develop technologies that can progress to advanced TRLs and result in commercial scale developments with more desirable business case economics.

There are several R&D opportunities that offer the most value for the money. For example, any programs that support development of the required infrastructure to provide hydrogen for a broad range of transportation and other end uses across KSA should be strongly considered. In the area of blue hydrogen, it will be especially important to find cost-effective solutions to capture and sequester (or utilize) the captured CO_2. In the area of green hydrogen, R&D programs that focus on improving the scalability and cost reduction of hydrogen/ammonia production from renewable energy sources will provide significant value. Electrolyzers using renewable power today are at small scale. To achieve greater quantities of hydrogen, large electrolyzer modules (typically 20 MW) must be manifolded together into units of 100+ MW capacity. Finally, development of cost-effective hydrogen storage and transportation solutions will be important for KSA, particularly for export.

Case study

Large-scale blue hydrogen projects

Air Products announced two large-scale blue hydrogen projects in 2021 – the Net-Zero Hydrogen Energy Complex in Edmonton, Alberta, Canada (expected onstream in 2024) and the Blue Hydrogen Energy Complex in Louisiana, USA (expected onstream in 2026). These projects, along with the existing Port Arthur Blue Hydrogen Plants, demonstrate three technology options for making blue hydrogen and utilizing or sequestering CO_2.

Port arthur retrofit SMRs

Air Products has been operating two blue hydrogen SMRs at the Valero refinery in Port Arthur, TX, USA since 2013. Combined, the two plants capture about 1 million tons/year of CO_2 which is injected into the Denbury pipeline to be used for EOR. This project received funding from the US Department of Energy as part of the American Recovery and Reinvestment Act. Each of the two SMRs was retrofitted with a CO_2 VSA (Air Products' patented technology) which captures 90% of the CO_2 from the syngas upstream of the hydrogen pressure swing adsorption (PSA) unit. As illustrated in Figure 17.4, the CO_2-depleted syngas is returned from the CO_2 VSA unit to the feed of existing hydrogen PSAs while the CO_2 produced from the VSA units in compressed, dried, and sent through a 13-mile pipeline and injected into Denbury's pipeline. The SMR plants are capable of producing hydrogen with or without CO_2 capture and are designed to maintain hydrogen production even if the CO_2 VSA trips offline to maintain hydrogen reliability.

Edmonton net-zero hydrogen utilizing ATR

Air Products has announced a $1.3 billion (CAD) net-zero hydrogen production and liquefaction plant in Edmonton, Alberta, Canada.[13] This project utilizes Haldor Topsoe ATR technology. Use of an ATR for hydrogen production offers an advantage

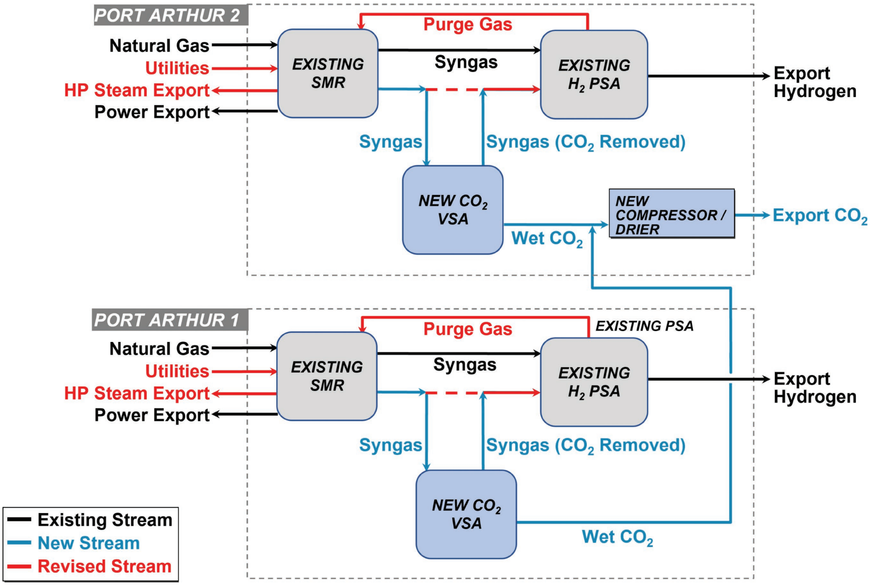

FIGURE 17.4 Block flow diagram of the Port Arthur SMR CO_2 capture plant.

Credit: Air products.

FIGURE 17.5 Top view of Air Products' CO_2 VSA trains used to remove more than 90% of the CO_2 contained in the reformer PSA feed gas. Credit: Air products.

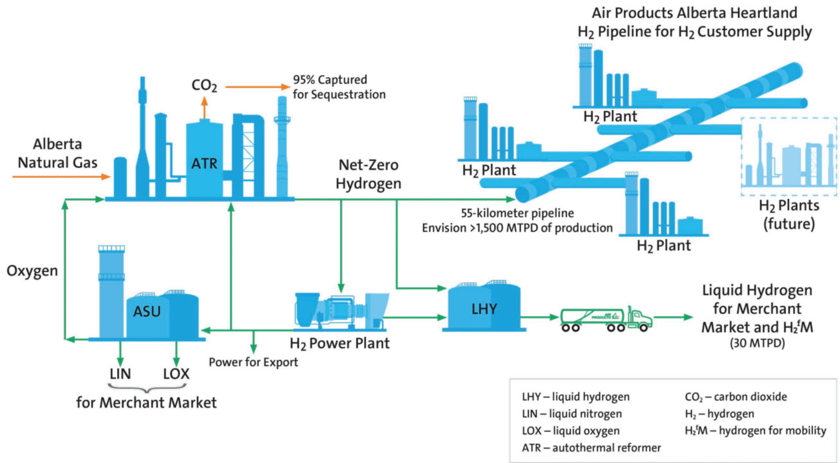

FIGURE 17.6 Illustration of Air Products' the net-zero hydrogen energy complex in Edmonton.

Credit: Air products.

over an SMR when high levels of CO_2 capture are desired. This is because the heat necessary for the reforming reaction is generated within the reactor vessel itself, thus minimizing or eliminating the need for a vented flue gas stream. As a result, the carbon capture system is able to remove 95% of the CO_2 from the complex. The CO_2 from the Edmonton project will be permanently sequestered by leveraging the Alberta Carbon Trunk Line. The facility will also include a power generation facility that will be fueled 100% by hydrogen, including NovaLT16 turbines from Baker Hughes, to produce clean electricity for the entire facility and to export to the grid. This will offset the 5% remaining CO_2 to achieve the net-zero hydrogen facility design. Figure 17.6 illustrates the Edmonton net-zero hydrogen energy complex.

Louisiana Blue hydrogen energy complex

Air Products has announced a $4.5 billion clean energy complex that will be built in Louisiana. This complex will produce over 750 million standard cubic feet per day of blue hydrogen.[14] This facility will utilize Air Products' POX technology. As with ATR technology, the heat for the reforming reaction in a POX reactor is generated within the reactor itself such that any venting of flue gas is minimized or eliminated. The facility will capture approximately 95% of the CO_2 generated by the process. The captured CO_2 will be compressed and transported by pipeline to sequestration sites. Over 5 million metric tons per year of CO_2 will be permanently sequestered in geologic pore space secured from the State of Louisiana approximately one mile (1.6 km) beneath the surface. A portion of the hydrogen will be compressed and supplied to customers by Air Products' extensive US Gulf Coast

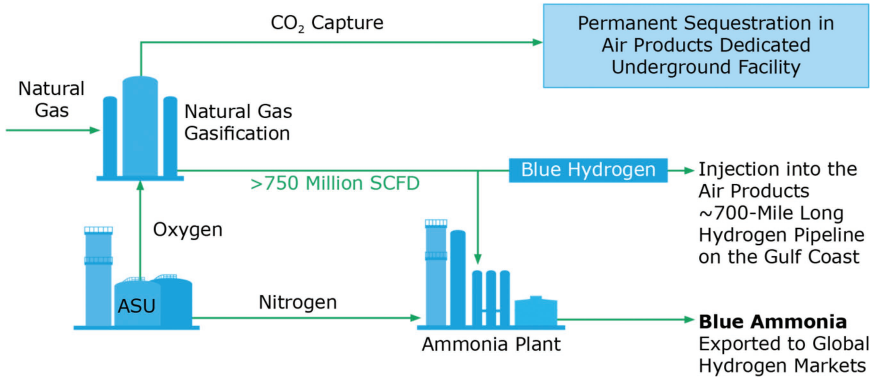

FIGURE 17.7 Illustration of Louisiana blue hydrogen energy complex.

Credit: Air products.

hydrogen pipeline network. The balance of the hydrogen will be used to make blue ammonia that will be transported around the world and converted back to hydrogen for transportation and other markets (Figure 17.7).

These three hydrogen projects highlight multiple approaches to decarbonizing hydrogen production. The SMR case represents a good option for retrofitting carbon capture into already existing assets. This enables ongoing use of existing infrastructure, while reducing carbon emissions in the near term. For new plant construction, ATR or POX technology is a good choice, particularly for high levels (>95%) of CO_2 capture. Regardless of the hydrogen technology employed, large quantities of captured CO_2 can be utilized for EOR or sequestered in underground geological formations both of which will provide a sink for the CO_2 for an extended period of time.

NEOM green hydrogen project

The Green Hydrogen Project or 'Company' was announced in July 2020. Air Products, ACWA Power, and NEOM have partnered together to develop a multi-billion world-scale green hydrogen production facility. The project will produce over 4 GW of renewable power from solar, wind, and storage to produce 650 tons per day of hydrogen by electrolysis (ThyssenKrupp technology) that will be converted into 1.2 million tons per year of green ammonia (Haldor Topsoe technology). The ammonia will be shipped overseas and cracked back into hydrogen for the mobility market globally (Figure 17.8). This project will save the world over three million tons of CO_2 emissions per year and eliminate smog-forming emissions and other pollutants from the equivalent of over 700,000 cars.[2]

Saudi Arabia has very low levelized cost of energy for solar and wind power which makes it a perfect location for this project. However, it is challenging to

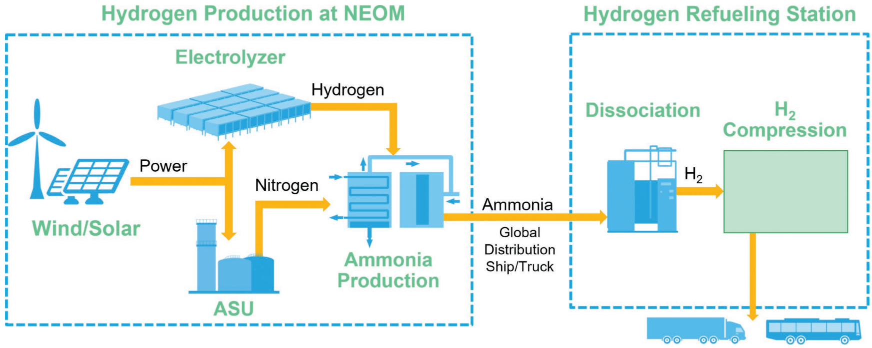

FIGURE 17.8 Illustration of the green hydrogen project at NEOM.

Credit: Air products.

cost-effectively transport hydrogen over great distances. Widely available commercial liquid hydrogen ocean transport does not currently exist and is not likely economical. It is for this reason that ammonia is being used as a hydrogen carrier for this project. Commercially available ammonia transportation is widely available. The ammonia can then be cracked back into hydrogen and nitrogen at either the use point or at a central location in close proximity to the use point. This enables green hydrogen/ammonia to be produced in a location such as KSA with low-cost renewable power and exported to locations around the world.

All of the technologies used in this project are proven technologies. The novel aspect is the integration of these technologies, particularly at this scale and utilizing ammonia to transport the hydrogen. Renewable power is intermittent by its nature which makes it a challenge to integrate with downstream equipment that must run continuously. It is expensive to install vast amounts of storage to dampen swings in renewable power; therefore, it is necessary to maximize operating flexibility in downstream equipment to minimize storage capacity. This same challenge exists in the reverse for onsite generation of hydrogen at fueling stations where the hydrogen production is continuous but the fueling station usage is intermittent.

Conclusion

Industrial gas companies, such as Air Products, are well positioned to deliver low-carbon hydrogen to a variety of industrial and commercial sectors to support the developing hydrogen economy. Although the required technology is available today to produce and deliver both blue and green hydrogen, government incentives and increased industrial development to move the technologies further down the cost curve will be key to success for the low-carbon hydrogen economy. Identifying areas to sequester the large quantities of CO_2 captured in blue hydrogen production will enable the immediate deployment of large-scale low-carbon hydrogen projects. Developing ways to increase scalability of water electrolysis and renewable energy production while reducing the overall cost will make green hydrogen cost competitive in the future. Within and beyond Saudi Arabia, dedicated government policies are necessary to eliminate any and all barriers to scaling up production and demand. This could drive a sustainable hydrogen economy and reduce the negative impacts that the ever-increasing quantities of CO_2 emissions are having on our planet.

Note

1 Carbon intensity is an estimate of the amount of carbon dioxide and other greenhouse gases emitted (on a CO_2-equivalent basis) per gigajoule hydrogen produced including all life cycle emissions.

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18

MISSION DECARBONIZATION

Large-scale commercial solutions for water electrolysis

Erika Niino-Esser, Malcolm Cook, and Ralph Kleinschmidt

Introduction

The chemical plant engineering entity thyssenkrupp Uhde owns an encompassing portfolio of chemical and process technologies, including ammonia, methanol, and synthetic fuels. For enabling sustainable chemical production at a large scale, the in-house technologies have been adjusted to allow for utilizing green routes.

Thyssenkrupp Uhde built the world's largest ammonia plant in Al Jubail in Saudi Arabia. The plant, the first of its kind, started operations with an ammonia production capacity of 3,300 tons per day in 2006. Owned by the SABIC Agri-Nutrients Company (formerly the Saudi Arabian Fertilizer Company), the plant has been producing 3,760 tons of ammonia per day since 2017, making it the largest ammonia plant globally (thyssenkrupp 2019). Furthermore, thyssenkrupp Uhde has provided the technology for three ammonia plants, each with a production capacity of 3,300 tons per day, for the Saudi Arabian Mining Company (Ma'aden) in Ras Al Khair (thyssenkrupp 2018). In October 2023, Neom's water and electricity subsidiary, ENOWA, awarded thyssenkrupp Uhde to supply a green methanol and methanol-to-gasoline plant. The production capacities for the green methanol plant at the Neom Hydrogen Innovation and Development Center will be 12 tonnes per day, while the capacity of the methanol-to-gasoline plant will be 35 barrels of gasoline per day. Saudi Aramco, who is a partner in the project, is going to utilize methanol for producing e-gasoline for various application for the light-duty transport sector.

To accomplish the mission for decarbonization, thyssenkrupp nucera offers world-leading technologies for high-efficiency electrolysis plants. thyssenkrupp nucera achieved a significant milestone by successfully completing the IPO in summer 2023. As a result, the company is now publicly listed on the Frankfurt stock market in Germany, with Saudi Arabia's Sovereign wealth fund, Public

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Investment Fund (PIF), having joined as an investor, holding approximately 6 % of the shares. thyssenkrupp nucera has already successfully installed more than 600 electrochemical projects over the last 50 years worldwide, with a total capacity of over 10 gigawatts. This existing experience has enabled a rapid development of thyssenkrupp nucera's water electrolysis for large-scale green hydrogen operations.

Saudi Arabia is also home to thyssenkrupp nucera's largest hydrogen chloride electrolysis plant with the Sadara Chemical Company (KfW IPEX Bank 2013). Moreover, most of the caustic soda production in Saudi Arabia is based on thyssenkrupp nucera's electrolysis technology. This technology is used at Sabic's affiliate Arabian Petrochemical Company (PETROKEMYA-North, formerly the Saudi Petrochemical Company), Sahara and Ma'aden Petrochemical Company, and the Basic Chemical Industries Company. A milestone for sustainable hydrogen production using water electrolysis was achieved by thyssenkrupp nucera in December 2021. The company has been awarded the project to provide more than 2 GW of alkaline water electrolysers for NEOM, the futuristic city-state in Saudi Arabia (Air Products Inc. 2021). With such a vast customer base in the Kingdom, it was only a matter of time before thyssenkrupp nucera established an office in Riyadh in September 2022. The company is actively expanding, particularly for the Neom Green Hydrogen Company project.

Ramping up water electrolyser capabilities

***NEOM Green Hydrogen Company (NGHC)*:** The NGHC will be one of the first locations where thyssenkrupp nucera's 20 MW water electrolyser plant will start its productive operation in 2024. This milestone project, funded by the German government, is also known as project "Element One." At the second stage, thyssenkrupp nucera will engineer, procure, and fabricate the water electrolysis with a capacity of more than 2 GW for green hydrogen production and is targeted to be online in 2026. NEOM Green Hydrogen Company, consisting of NEOM, ACWA Power and Air Products, will operate the facility for the sustainable hydrogen and ammonia production (Air Products Inc. 2021).

***Alkaline water electrolysis from thyssenkrupp nucera*:** Water electrolysers are electrochemical devices where purified water as well as electricity is fed to produce hydrogen and oxygen. Water electrolysers are divided into four main technologies: alkaline water electrolysis (AWE), polymer electrolyte membrane (PEM), solid oxide electrolyser cell, and anion exchange membrane. They vary in the electrolytes as well as operating parameters, which in turn influences the selection of different materials and components. AWE and PEM are already available in commercial scale. A water electrolysis system with a capacity of more than 10 MW currently costs between 500 and 1,000 USD/kW for AWE technology or 700 and 1,400 USD/kW for PEM. These prices are expected to fall below 200 USD/kW by 2050 (IRENA 2020).

Thyssenkrupp nucera offers AWE and is continuously working upon improving the technology to achieve performance increases as well as cost reductions. Nonetheless, further policies and substantial investments are necessary if the global industry sector aims to decarbonize its processes through hydrogen utilization. IRENA's Transforming Energy Scenario, which is in line with the Paris Agreement's 2°C trajectory and translates into 9.5 giga tons of carbon dioxide remaining until 2050, will require a water electrolyser capacity of 270 GW by 2030 (IRENA 2020). Much larger volumes of hydrogen are required, therefore, in turn, require a larger electrolyser capacity. In 2020, the world was at a capacity of 0.2 GW of water electrolysis (IRENA 2020).

Over the past few years, thyssenkrupp nucera has developed modules for AWE up to a standard size of 20 MW. Consequently, the company is not only able to reduce the footprint of its plant, but it has also achieved a significant cost reduction. Picturing the current situation where electrolysers of several hundred megawatts are needed, we only have to multiply these 20 MW modules. Further cost-reductions can be realized with numbering up the modules to big plant sizes (Figure 18.1).

***German Hydrogen Strategy*:** thyssenkrupp nucera has already built up an annual supply capacity of 1 GW of electrolysers in Germany and thyssenkrupp is involved in three hydrogen lead projects that are funded by the German Federal Ministry of Education and Research (BMBF). The projects are H_2Giga, H_2Mare, and TransHyDE and have been initiated in the context of implementing the German National Hydrogen Strategy (German Federal Ministry of Education and Research 2022). Through H_2Giga, the automated and serial production of water electrolysers will be enabled. Within four years until 2025, thyssenkrupp will expand the manufacturing capacity to 5 GW. The aim of H_2Mare is to explore the generation of green hydrogen and other power-to-X products while utilizing offshore wind energy directly at the sea. Minimizing production costs will be achieved via the direct coupling of offshore wind energy and water electrolysis. thyssenkrupp is

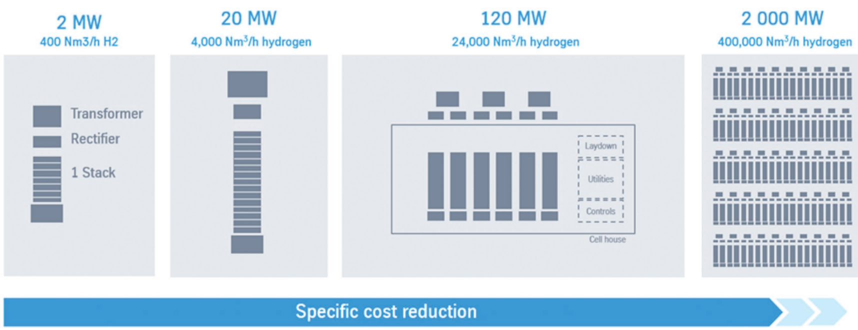

FIGURE 18.1 Schematic layout of thyssenkrupp's water electrolysers for capacities of 2, 20, 120, and 2,000 MW.

Source: thyssenkrupp (2021).

involved in the sustainable production of synthetic fuels, methane, green ammonia, and green methanol at sea for H_2Mare and conversion technologies such as ammonia cracking in TransHyDE. In the latter project, several technologies for hydrogen transportation will be developed, evaluated, and demonstrated. Even though Germany will produce hydrogen within the country, a large amount needs to be imported from wind- and sun-rich regions. Therefore, an efficient infrastructure for transporting hydrogen is required (German Federal Ministry of Education and Research 2022; thyssenkrupp 2021).

Decarbonizing thyssenkrupp's steel sector

In 2019, thyssenkrupp has established a climate strategy that aims for reaching climate-neutrality by 2050. For decarbonizing its steel production, thyssenkrupp follows two different paths to turn decarbonization into reality:

1 Carbon direct avoidance (CDA) through direct reduction of iron while using hydrogen (DRI).
2 Carbon capture and utilization (CCU) by converting steel mill gases into base chemicals, such as methanol or ammonia.

Direct reduction of iron: In March 2023, thyssenkrupp Steel has awarded a contract to SMS group for engineering, delivery, and construction of a hydrogen-powered direct reduction plant in Duisburg, Germany. This marks the start of one of the biggest industrial decarbonization projects worldwide. The production capacity will be 2.5 million metric tons of directly reduced iron and will save over 3.5 million metric tons of carbon dioxide per year. The plant will require around 143,000 metric tonnes of hydrogen per year from the start of operation expected to be 2029. In July 2023, thyssenkrupp Steel got the confirmation from both federal and state government to receive funding totaling around 2 billion euros. This funding ensures the realization of the project as the order volume for SMS group alone is over 1.8 billion euros and thyssenkrupp's own investment is around 1 billion euros (thyssenkrupp 2023a, b).

Carbon2Chem® project: Since 2016 the CCU approach is being investigated together with several partners in the publicly funded Carbon2Chem® project, which is located next to thyssenkrupp's steel production site in Duisburg, Germany. Carbon2Chem® is a research project funded by the German government, through which CCU is being applied via steel mill gases and hydrogen from water electrolysis (thyssenkrupp 2020). The plants, where major waste gases are generated during steel production, consist of blast furnaces, coke ovens, and converters. The combined three gas streams from these plants contain around 43% nitrogen, 25% carbon monoxide, 21% carbon dioxide, and only 8% of hydrogen. The rest are other contaminants, which are harmful for the catalysts during chemical production. For utilizing nitrogen for ammonia production and carbon-containing gases for methanol and higher alcohols, an external source of hydrogen is required. The use of steel mill gases from steel production in the chemical production is extremely innovative but relatively new. For this reason, Carbon2Chem® plants have so far only been installed on a demonstration, pilot, and laboratory scale but are now ready for the next steps of scaling up.

To satisfy the demand of hydrogen at the Carbon2Chem® project, a water electrolysis plant with a capacity of 2 MW has been installed. This demonstration plant is the first megawatt-scale AWE from thyssenkrupp nucera. Since its operation from April 2018 onward, the current cell design for AWE has been qualified at this test facility. Continuous improvement of cell components, such as electrode coating or separators, has been conducted under real operating conditions. One such real operating condition includes the intermittent operation simulating a renewable energy source. Together with E.ON, a German energy company, it has been shown that thyssenkrupp's AWE approach meets the technical requirement to participate in the German primary reserve. Primary reserve control is the most technologically challenging requirement to meet for the German grid system. Therefore, thyssenkrupp nucera's AWE responses are very suitable for dynamic operation and for direct connection with renewable energy sources.

Path forward at thyssenkrupp nucera and technological challenges regarding seawater electrolysis

The cell design for the alkaline water electrolysers from thyssenkrupp nucera is based on its own chlor alkali electrolysis technology and has been adjusted for the electrochemical production of hydrogen and oxygen. The strategy related to how thyssenkrupp nucera is going to further develop its cell elements for AWE in the upcoming years is explained in Figure 18.2.

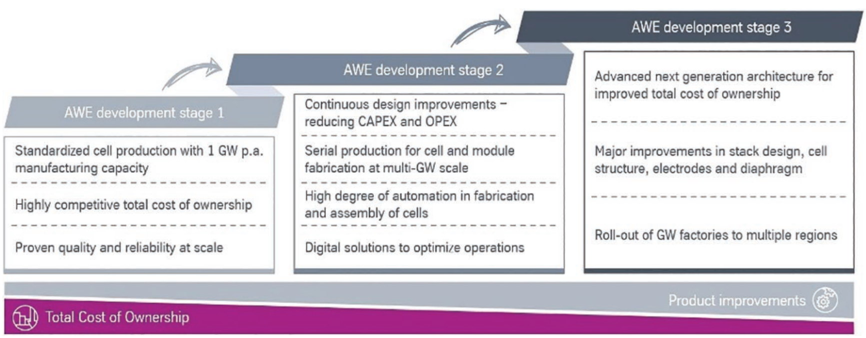

FIGURE 18.2 Strategic roadmap for thyssenkrupp nucera's alkaline water electrolysis technology as of January 2022.

Source: thyssenkrupp (2022).

The current cell design under "AWE 1.0 technology" is market ready, and standardized cell elements can already be produced with 1 GW of manufacturing capacity per annum. With years of operational experience gathered through Carbon2Chem®, the electrolyser has a high quality and is also highly reliable during dynamic operation. Moreover, due to the continuous improvements, the current electrolyser achieves already a competitive total cost of ownership. The short-term development within the next two to three years aims at reducing both CAPEX and OPEX, which then leads to the next generation cell design under "AWE 1.x technology." The aim is to deploy the new design for the previously mentioned H_2Giga project with its annual manufacturing capacity of 5 GW from 2025 onward. In the mid-term (four to five years), major improvements in stack design are expected to be implemented leading to the "AWE 2.0 technology." This can include any type of disruptive technologies in the field of water electrolysis. For the implementation of "AWE 2.0 technology," a further increase of the cell manufacturing capacity is planned, which also considers an expansion into multiple regions.

The ongoing efforts in R&D will not change the fact that water is a crucial resource for the deployment of water electrolysers. Based on stoichiometric calculation, 9 kg of distilled water is theoretically required to produce 1 kg of hydrogen. In practice, however, water consumption is even higher due to process inefficiencies which lead to an estimate of 18–24 kg of water per kg of hydrogen produced (IRENA 2020). Consequently, the usability of seawater and the further development of desalination technologies will continue to play a significant and growing role to overcome water scarcity in the MENA region.

Seawater electrolysis is a quite unexplored research topic but is receiving growing attention (Dionigi et al. 2016). Via this technology, seawater could be directly fed into the electrolyser to split water into hydrogen and oxygen. The main technical challenge is the high content of contaminants in seawater during the electrolysis, that is, primarily chloride, which triggers the undesired and poisonous chlorine (at low pH) and hypochlorite (at high pH) formation over the desirable oxygen production. Even traces of chloride ions in commercial electrolysers with common potentials (1.8–2.4 V) would result in the electro-oxidization to hypochlorite ions, which harm the current catalysts and limit the long-term stability.

The chemical challenge is to design robust and selective materials for both the electrodes and separators. Research has identified selective and active catalytic materials to suppress undesired electrochemical processes (Dresp et al. 2019). As an example, it was found that the nickel-iron (NiFe)-layered double hydroxide catalyst achieves a high selectivity for oxygen evolution. However, the measurements have been conducted at relatively low current densities of 10 mA/cm^2, and the authors state that an extended testing is needed to evaluate the long-term stability in commercial devices (Dionigi et al. 2016). In addition, developing a separator to increase the stability of direct seawater electrolysis seems to be another bottleneck of the technology (Dresp et al. 2019).

Therefore, the short- and mid-term perspective will be the operation of water electrolysis plants by utilization of commercial desalination. In the future, when cell components are suitable for the long-term and stable operation of seawater electrolysis, then electrolysers can be retrofitted for direct use of seawater, making the freshwater of the desalination plants available for other usages. The long-term stability of materials is crucial for deploying seawater electrolysers in the future to avoid a shortened lifetime of the cell components and requires an ongoing analysis of cost-effectiveness of a regular maintenance regime of the electrolyser or water purification technologies, such as reverse osmosis.

A futuristic approach with a floating desalination plant

For the commercial desalination of seawater, two approaches are most prevalent. The first one is conducted through thermal desalination, using heat to evaporate and condensate water. The second method is called reverse osmosis, a mechanical separation, where seawater is pressurized through a membrane, so that mainly salt but also other components are filtered out of the water. Although membranes suffer from relatively short life and therefore high replacement costs, advancements in feedwater pretreatment as well as the gains from operational experience ensured that this method become a predominant technology with a 60% share of global desalination capacity (Advisian-Worley Group n.d.). At present, around 95 million m^3 of water per day is produced through desalination worldwide. However, brine amounting to around 142 million m^3 per day is left as waste (Jones et al. 2019). This large volume of residues is a downside of all desalination technologies. At least for reverse osmosis, the production of brine is less compared with thermal approaches. Another factor to mention is the high amount of electricity needed for desalination, which is generated currently by fossil fuels. Once again, reverse osmosis is more advantageous comparing to the thermal desalination since operating costs for thermal energy are usually higher in comparison to energy for mechanical separation (Der Tagesspiegel 2021).

A new approach is seen in the concept of "Floating WINDdesal" (FWD), comprising a seawater desalination plant and an offshore wind turbine, both supported by a floating semisubmersible structure (Offshore Magazine 2021). The technical ideas of the floating desalination plant are based on drilling platforms from the oil industry, which are usually stabilized with legs reaching deep into the seabed. The FWD, on the contrary, is equipped with anchors, which makes a relocation relatively simple. Like an oil platform, the floater can be pulled with a special transport ship to the place of use. The technical implementation will take some time; but once the floater is in operation, it should be able to desalinate 30,000 m^3 of water per day (Der Tagesspiegel 2021). The desalinated water will be pumped to an onshore storage facility by submarine pipes and afterward will be fed into the water distribution system (Offshore Engineer 2021). According to SYNLIFT, even

FIGURE 18.3 Floating WINDdesal plant with a capacity of 30,000 m³/d for the production of desalinated water (left side: full view including the wind turbine, right side: close-up of the platform) (Synlift n.d.).

the brine production is less critical with the FWD, since the caustic solution can be diluted deep into the ocean (Der Tagesspiegel 2021). The design of the "FWD" is depicted in Figure 18.3.

The development of the FWD is supported by a European Industry initiative. In December 2020, SYNLIFT and its partner NTCC have submitted a proposal for the state tendering process realizing the demonstration plant FWD in Saudi Arabia. The Saudi company Saline Water Conversion Corporation (SWCC), the world's largest player on the desalination market, has expressed its interest in supporting the project as an off-taker, and in November 2021, SWCC and SYNLIFT have signed a framework agreement to collaborate in Saudi Arabia (Asaba 2018) with the FWD reference project as a first cooperation activity (Synlift n.d.).

The objective of the project is to combine desalination with renewable energy. Even though renewable energies are intermittent, and storage demand must be covered through batteries or water containers, this concept comes along with advantages in terms of profitability. According to SYNLIFT, desalination costs of USD 0.67–0.85 (using wind energy) or rather USD 0.97–1.21 (applying solar energy) per m^3 of freshwater are possible in regions with a lot of wind and solar energy (exchange rate: USD/EUR = 1.21) (Der Tagesspiegel 2021). These prices are below average, considering the global average desalination cost of USD 2.90 per m^3 of water after deducing the subsidies for fossil fuels (cost in 2015). Recent studies by the Technical University of Lappeenranta in Finland also reveal significant cost reduction potentials by decarbonizing the desalination sector (Der Tagesspiegel 2021).

After having reviewed different technologies in this chapter, the main approaches for the utilization of seawater to produce hydrogen can be summarized as follows:

- A commercial desalination plant combined with a commercial water electrolysis (i.e., thyssenkrupp nucera's AWE)
- A mobile desalination, FWD, combined with a commercial water electrolysis
- Seawater electrolysis plant

Given the nascent developments, a techno-economic analysis, analyzing which one is the most promising, is not plausible currently. Especially for the seawater electrolysis, there are too many uncertainties. Besides the current lack of suitable materials to use seawater directly for water electrolysis, there are several other aspects that need to be studied in more detail. The impact of large-scale application, influence of higher current densities, and long-term stability has not been analyzed, yet. In addition, all products coming out of the seawater electrolysis system should be carefully examined. Depending on the impurities of the produced gas streams, they may require additional or special treatment, which might lead to increasing operating cost, therefore an unattractive business case.

The FWD, on the contrary, is based on many well-known technologies, such as the wind turbines and the reverse osmosis. Therefore, it is expected that this development project will be realized soon. At this stage, there are not enough information available; that is why, an in-depth economic evaluation is not possible.

Assuming a seawater consumption of 20 kg for producing 1 kg of hydrogen, thyssenkrupp nucera's 20 MW water electrolyser will need 175 m^3/d of seawater for a constant full load operation. Therefore, the FWD with a capacity of 30,000 m^3/d will be sufficient to cover the demand of around 3.4 GW of water electrolysers. Since the operating costs of the FWD are expected to be less than the conventional desalination, the business case should be attractive. An additional benefit will be the operation based on renewable energies, which fits perfectly in the green hydrogen production ambition. Therefore, the FWD in combination with thyssenkrupp's water electrolysis can be assumed to be an attractive business case. Nevertheless, an in-depth techno-economic analysis will be required to validate this assumption.

Conclusion

thyssenkrupp is highly active in the decarbonization and green chemical production due to its strong technology portfolio, which includes large-scale AWE as well as green chemical plants. As the Kingdom of Saudi Arabia is already home for thyssenkrupp's technologies, such as large ammonia plant and the largest HCl electrolysis plant worldwide, the gigawatt-scale project in NEOM will create a new chapter in history books. The sustainable production and utilization of water facilitate the sustainable generation of green hydrogen. thyssenkrupp nucera has further expanded the presence in Kingdom of Saudi Arabia by establishing a new office. We see this as another important milestone for us in the partnership with the Kingdom of Saudi Arabia in the global energy transformation.

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19

ROLE OF CARBON CAPTURE IN ENABLING A BLUE HYDROGEN ECONOMY

Deoras Prabhudharwadkar, William Roberts, Robert Dibble and Larry Baxter

Introduction

Hydrogen production is dominated by fossil fuel-based methods. Globally, 70 million tons of pure hydrogen is produced annually, 76% using natural gas and 23% using coal. The remaining 1% comes from oil or electrolysis. This results in annual carbon dioxide (CO_2) emissions of approximately 830 million tons (IEA 2019). Steam methane reforming (SMR) is the most widely deployed technique for producing hydrogen from natural gas (partial oxidation and auto-thermal reforming are the other two lesser used techniques). However, the SMR process is carbon-intensive, producing almost 9–10 kg of CO_2 per kg of hydrogen when natural gas is used as both a feedstock and a fuel for SMR. Carbon capture from hydrogen production facilities as well as its storage and utilization turn gray hydrogen to blue. Figure 19.1, which shows a simplified block diagram of SMR, illustrates the possible locations from which CO_2 can be captured (Collodi 2010; IEAGHG 2017). Table 19.1 summarizes the conditions relevant to the CO_2 capture at these locations.

The feed-containing methane and steam are supplied to the reformer furnace in which they react in the presence of a nickel-based catalyst to form syngas (a mixture of carbon monoxide and hydrogen). The furnace is fired using separate streams of fuel and air, as shown in Figure 19.1. Carbon monoxide reacts with the residual steam in the shift reactor to maximize hydrogen production. The products of this reaction are CO_2 and hydrogen. A pressure-swing adsorption (PSA) system is deployed downstream of the shift reactor to extract pure hydrogen from the product of the reaction. The adsorbent can be a packed bed of zeolite, activated carbon, or silica/alumina gel. Impurities separated from the hydrogen are collected in the tail gas, which also forms a part of the reformer fuel.

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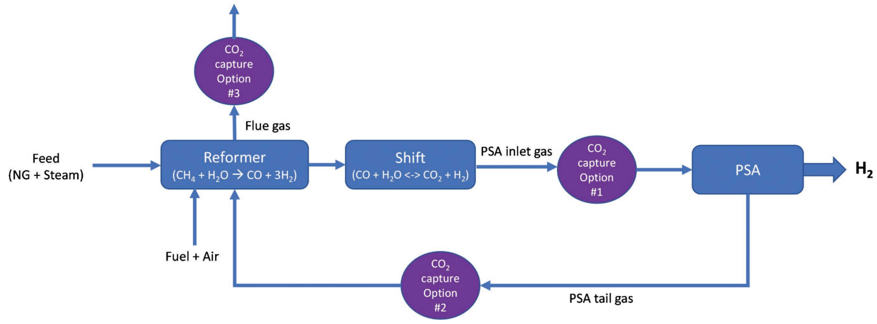

FIGURE 19.1 CO_2 capture possibilities in an SMR plant.

Source: Collodi (2010); IEAGHG (2017).

TABLE 19.1 Comparison of the CO_2 capture options from SMR

CO_2 capture option	*CO_2 concentration (% mol) wet basis*	*CO_2 partial pressure (bara)*	*Achievable CO_2 capture*
PSA inlet	15–16	3.4–3.7	60%
PSA tail gas	45–50	0.6–0.67	55%
SMR flue gas	19–20	0.2	90%

The Global CCS Institute (2021) summarized the latest published costs of green hydrogen using renewables-driven electrolysis and blue hydrogen using fossil fuels with carbon capture. While the average cost of green hydrogen using dedicated renewables is about $5.50/kg (ranging from $2.30/kg to $7.70/kg for an electricity price range of 2.2–10 cents/kWh), that of blue hydrogen from SMR is $2/kg (ranging from $1.60 to $2.40 for a gas price of $3–9/GJ). Hence, under the existing infrastructure and level of cost competitiveness, blue hydrogen is set to be the near- to mid-term solution for delivering low-carbon hydrogen until green hydrogen facilities catch up in scale and cost (Global CCS Institute 2021).

In the remainder of this chapter, we first estimate the scale of CO_2 capture needed to decarbonize the majority of the power sector in Saudi Arabia using blue hydrogen. We then assess a promising carbon capture technology being developed at King Abdullah University of Science and Technology (KAUST) in Saudi Arabia.

Decarbonizing the power sector in Saudi Arabia using blue hydrogen

Between 2013 and 2017, the electricity generation capacity in Saudi Arabia grew by approximately 25%, increasing from 71 GW to 89 GW (Electricity & Cogeneration Regulatory Authority 2017). From 2017 to 2019, the capacity slightly declined to approximately 85 GW (including 0.4 GW of new renewables) (Electricity &

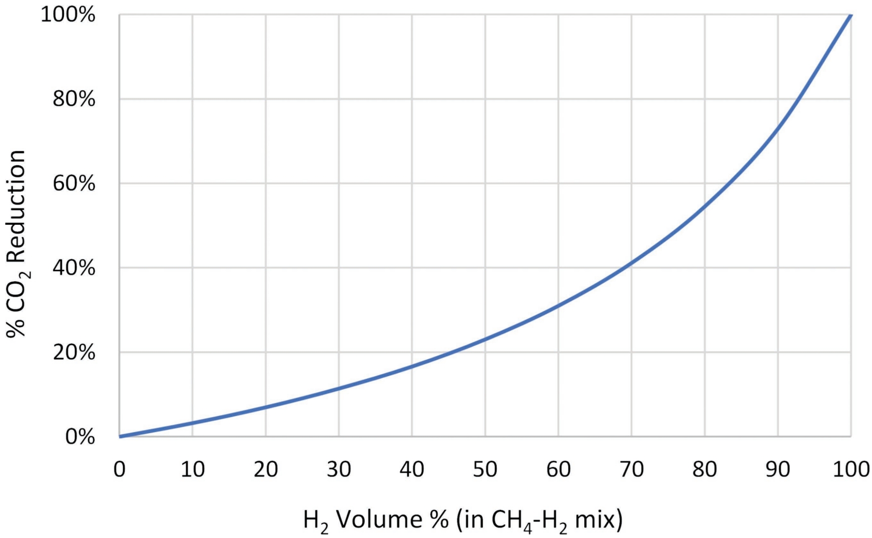

FIGURE 19.2 CO_2 emissions reduction as a function of the hydrogen content in the fuel mix of a gas turbine.

Source: Authors.

Cogeneration Regulatory Authority 2019). Approximately 37 GW of this 85 GW installed baseload generation is either a simple or combined cycle power plant operating on natural gas. This fleet presents a natural first choice for decarbonizing hydrogen as the fuel, either fully or as a blend with natural gas.

Hydrogen blending into natural gas fuel is limited by the technology readiness of the various categories of gas turbines. For example, general electric's B- and E-class gas turbines are capable of handling 100% hydrogen as the fuel, while the F-class can handle up to 65% of hydrogen by volume (GE 2021). The latest high-efficiency H-class machines can achieve a 50% hydrogen blend by volume. Figure 19.2 shows the reduction in CO_2 emissions for a given percentage of hydrogen in the fuel mix, illustrating that an F-class plant with 60% hydrogen could reduce CO_2 emissions by approximately 35%. By contrast, the reduction in CO_2 emissions attained for an H-class plant with 50% hydrogen would be approximately 25%. Figure 19.3 shows the mass flow rate of hydrogen scaled by the flow rate required for 100% hydrogen for a given hydrogen blend by volume. This nonlinear trend is driven by the differences in the densities and calorific values of hydrogen and CH_4. The information in Figure 19.3 is used in this chapter to analyze the fleet-wise hydrogen requirement for power generation in the Kingdom of Saudi Arabia.

Global energy observatory's data on the power plants in the Kingdom are used to determine the distribution of the gas turbine fleet in Saudi Arabia. We filter the data to limit our focus to gas turbines that have a unit capacity of at least 30 MW

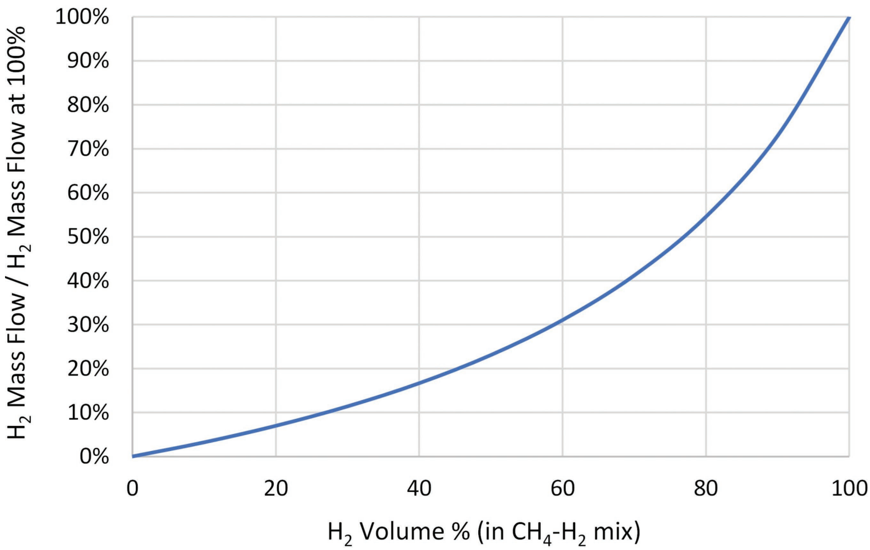

FIGURE 19.3 Hydrogen mass flow requirement as a function of the volume blending in the natural gas fuel mix.

Source: Authors.

(i.e., heavy-duty turbines). This filtered fleet accounts for 35 GW of capacity (approximately 75% of the total) from 26 power plants. Table 19.2 lists the fleet-wise breakdown of the capacity and fuel requirements. The following assumptions underlie the analyses:

1 Hundred percentage hydrogen is used in E-class gas turbines compared with 60% (by volume) for F-class turbines.
2 The performance of gas turbines (output and heat rate) is similar when switched to hydrogen.
3 The capacity factor of the plant is assumed to be 85%.
4 Catalog ratings of gas turbines are used to estimate performance (actual performance depends on the site configuration).
5 All the hydrogen supplied from the SMR process has a CO_2-to-hydrogen mass ratio of 9.
6 The hydrogen lower heating value is 51,600 Btu/lb (or 120 MJ/kg).

The purpose of Table 19.2 is to estimate the scale of hydrogen required and associated carbon capture for the gas turbine fleet in the Kingdom**.** As shown in Table 19.2, approximately 12 million tons of hydrogen per year would be required to meet such a scenario and the associated CO_2 capture would reach 107 million tons/year. The exhaust from natural gas power plants would contain approximately

TABLE 19.2 Hydrogen supply and CO_2 capture requirements for decarbonizing a gas turbine fleet in Saudi Arabia

Gas turbine fleet type	*7EA simple cycle (GE)*	*7F simple cycle (GE)*	*7E combined cycle (GE)*	*7F combined cycle (GE)*	*6B simple cycle (GE)*	*GT11D5 simple cycle (ABB)*	*SGT6–5000F combined cycle (Siemens)*	*Total*
No. of units	75	11	60	38	15	27	12	238
Rated output (MW)	85.4	198	130	305	44	73.3	387	
Rated heat rate (Btu/kWh)	10,417	8,840	6,800	5,715	10,180	10,866	5,725	
Total fleet output (MW)	6,405	2,178	7,800	11,590	660	1,979	4,644	35,256
Source of performance data	Gas Turbine World (2020)	Chase & Kehoe (GER-3574G)	Chase & Kehoe (GER-3574G)	Gas Turbine World (2020)	Gas Turbine World (2020)	Schneider, Navrotsky, and Harasgama (1998)	Gas Turbine World (2020)	
Hydrogen (tons/year per unit)	58,230	34,370	57,862	34,228	29,319	52,135	43,506	
Hydrogen (million tons/year)—full fleet	4.37	0.38	3.47	1.30	0.44	1.41	0.52	11.89
CO_2 capture from SMR (million tons/year)	39.31	3.4	31.25	11.71	3.96	12.67	4.7	106.9

4% CO_2 compared with 20% in the exhaust of SMR. This means that the energy requirement and cost of CO_2 capture would be lower when undertaken by SMR than post-combustion capture from the exhaust of natural gas power plants. However, post-combustion capture has its benefits such as easy retrofitting with no major modifications to the plant infrastructure (Global CCS Institute 2021). KAUST is therefore focusing on developing an easy bolt-on retrofit technology in collaboration with Sustainable Energy Solutions in the United States, which can be applied to both scenarios. This is discussed in detail in the following section.

Saudi Arabia emits 526 million tons of CO_2 emissions from fossil fuels annually, with over 150 million tons (approximately 30%) coming from the energy sector (KAPSARC 2020). Under the Nationally Determined Contributions of the Paris Agreement, Saudi Arabia pledged to abate up to 130 million tons of CO_2 by 2030 (Climate Transparency 2020). A comparison of these numbers with the above analyses shows that converting the gas turbine fleet to blue hydrogen is a potential pathway toward reaching this target. However, this conversion requires the aggressive scaling up of hydrogen production facilities (likely a mixture of green and blue hydrogen) as well as carbon capture and storage (CCS). The green hydrogen project recently announced by Neom has an expected hydrogen capacity of 650 tons/day (approximately 0.25 million tons/year) (Global CCS Institute 2021). Saudi Arabia has active utility-scale carbon capture projects amounting to 1.3 million tons of CO_2 per year, including Saudi Aramco's 0.8 million ton Uthmaniyah project and SABIC's 0.5-million-ton project. This means that the above scenario would require an ambitious two-orders-of-magnitude scaling up in Saudi Arabia's capture and storage/utilization capacity to turn it into reality.

Policy incentives, accelerated research to advance technology, and cost reductions will be the key drivers of CCS technology in the future. Under its G20 presidency in 2020, Saudi Arabia announced a circular carbon economy strategy to focus on its 4Rs (reduce, reuse, recycle, and remove; Arab News 2020) and a national program committee is identifying potential projects under each of these Rs to accelerate the reduction in CO_2 emissions.

Carbon capture technology for blue hydrogen

Carbon capture technologies can be broadly classified into pre-combustion, post-combustion, and oxy-combustion, and various solutions at different technological readiness levels (TRLs) exist under each category (Raza et al. 2019; Sifat and Haseli 2019; Songolzadeh et al. 2014). Pre-combustion technology removes CO_2 from the fuel before it is fed into the energy generation or combustion system. SMR with CO_2 capture falls under this category. Although these systems have smaller footprints because they deal with higher concentrations of CO_2, they change the combustion system in the downstream application and are thus more intrusive. Post-combustion systems, on the contrary, do not need to change the combustion system because CO_2 is captured after the fuel is burned, making these systems retrofittable. However, they have a larger footprint because they deal with lower concentrations of CO_2 in the exhaust, which also contains nitrogen, oxygen, water vapor, and other pollutants. Oxy-combustion systems simplify post-combustion capture because they use only oxygen for combustion instead of air. As a result, the exhaust mainly contains CO_2 and water vapor, which, when condensed, leads to only CO_2 in the exhaust, and this can be easily tapped for capture. These systems also require air separation units to separate oxygen from air molecules, while the combustion system must be modified because air is replaced by oxygen as the reactant.

Globally, four commercial-scale SMR facilities are equipped with CCS technology: these facilities produce approximately 0.88 million tons of blue hydrogen annually (Global CCS Institute 2021) and capture and store about 4 million tons of CO_2 every year (Energy Technology Perspectives 2020). Carbon capture using the absorption of CO_2 into an amine-based solvent, which is the most developed carbon capture technology, is used at three of these four sites (Air Product's Port Arthur plant uses vacuum-swing adsorption; IEAGHG 2018); however, this technology has a high energy penalty (25%–30%), as its operation requires a combination of heat and electricity. Other technologies are thus emerging, including one that cryogenically separates CO_2 from flue gas (Hoeger, Burt, and Baxter 2021; Rodrigues et al. 2021). This emerging technology relies on the separation of CO_2 from a gas mixture through phase-change processes.

The phase diagram of CO_2 in Figure 19.4 shows that CO_2 has a high triple point at which the three phases (i.e., gas, solid, and liquid) coexist at approximately 5.1

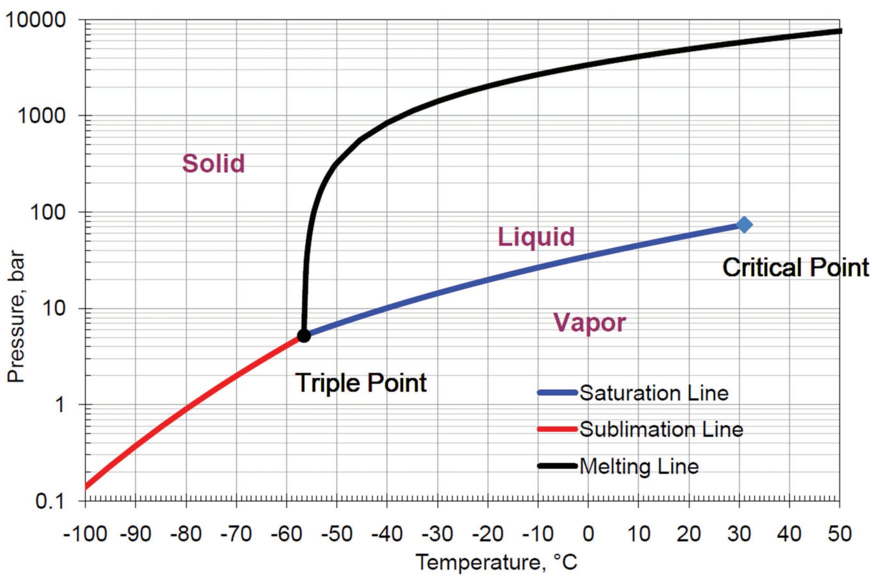

FIGURE 19.4 Phase diagram of CO_2.

Source: Raza et al. (2019)

bar; hence, separating CO_2 by condensing liquefaction can occur only at pressures above 5 bar. At pressures below the triple point, CO_2 separates by forming a solid (commonly known as “dry ice”), directly from the vapor form, through a process known as anti-sublimation or desublimation. At atmospheric pressure, pure CO_2 desublimates at about −78.5°C. When dealing with a mixture of gases, since the partial pressure of CO_2 is below the total pressure, the desublimation temperatures can be much lower, typically in the range of −120°C to −140°C.

Another emerging CO_2 capture process, based on the liquid separation of CO_2, is Air Liquide’s Cryocap™ process designed to separate CO_2 from the high concentration CO_2 in the hydrogen mixture in the PSA tailpipe, as indicated by Option 2 in Figure 19.1 and Table 19.1 (Terrien et al. 2014). This technology has been piloted in France, where it has managed to capture 300 tons of liquid CO_2 per day from an SMR plant with a daily capacity of approximately 100 tons of hydrogen. As shown in Table 19.1, only approximately 55% of the CO_2 produced from SMR can be captured under Option 2, which is the most attractive location owing to its high CO_2 concentration. However, to reduce the carbon footprint of SMR and thus be able to call the produced hydrogen truly “blue,” the majority of the CO_2 must be captured at the flue gas exit, as shown in Option 3 in Table 19.1, using a technology that can handle diluted CO_2–gas mixtures (<15% volume fraction).

KAUST has partnered with Sustainable Energy Solutions, a part of Chart Industries based in Utah, to develop and demonstrate an innovative cryogenic carbon capture (CCC) technology at a pilot scale of a 1 ton (short ton)/day CO_2 capture rate (TRL 6). In line with the Kingdom’s Vision 2030, CCC technology being developed in the country offers the potential to generate high-quality research, localize the supply chain, and obtain global investment, which could all grow both employment levels and GDP. Further, this CCC technology could serve as a hub for core innovations that could be applied in multiple sectors and large markets, including direct air capture, natural gas treatment, low-pressure dehydration, direct contact heat exchangers, heat exchanger processes, and CO_2 capture.

CCC technology has several technoeconomic advantages over conventional amine-based absorption technologies:

- Amine-based technologies require a steam source, usually from burning fossil fuels, which increases the energy penalty, site size, and system cost. However, the CCC process requires only electricity, making it possible to power the technology using only renewable energy. This can decrease the site size and lower the overall system cost.
- CCC can handle pollutants such as NO_X, SO_X, Hg, and other pollutants to which alternative carbon capture technologies are sensitive (resulting in performance degradation over time). Indeed, it may eventually replace SO_X, NO_X, and Hg controls. Although this is not relevant to SMR, it makes the application of CCC technology versatile.
- CCC recovers a significant amount of usable water from gas streams, thus requiring minimal water for operation.

- Cryogenic liquids can be produced and stored using surplus electricity (that occurs in the daytime for photovoltaic power), which can later be used for CCC when demand is high. Thus, CCC offers grid-scale integrated energy storage that allows for the better adoption of renewables and load leveling (Fazlollahi and Baxter 2015; Safdarnejad et al. 2015, 2016).
- CCC easily retrofits on any stationary source of CO_2 emissions (e.g., power plants, industrial plants, and chemical plants) without the need for new steam generators or upstream process integration that alternatives usually require.
- There are no toxic chemical emissions (e.g., the loss of amines when carried away by the exhaust gas leaving the scrubber/absorber).
- The output of the CCC process is ultra-high-purity (>99.99%) liquid CO_2 at pressures and temperatures that can be readily transported.

CCC technology overview

Process description

Figure 19.5 illustrates a simple flowchart of the CCC process. The exhaust gas enters the bottom left and is cooled and dried before CO_2 capture. The system developed by Sustainable Energy Solutions simultaneously cools and dries gas with a minimal pressure drop, but these unit operations can also be performed using conventional technology. The flue gas enters the bottom of the desublimating heat

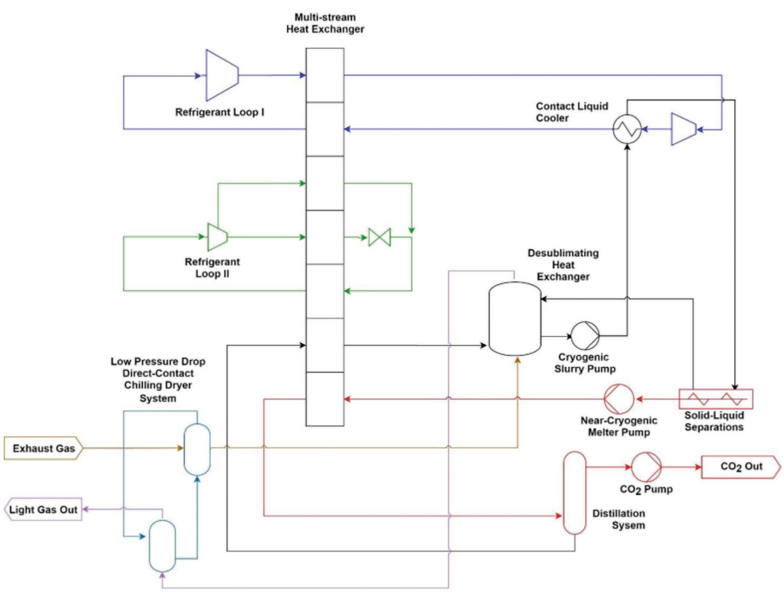

FIGURE 19.5 Flow diagram of the CCC process.

Source: Hoeger et al. (2021).

exchanger (DHX) at approximately −100°C depending on the CO_2 content and pressure. A DHX is a counter-flow spray tower with cold droplets of contact liquid (flowing from the top against the upward-flowing flue gas). The cold droplets of the contact liquid warm as they cool the flue gas and collect the desublimating CO_2 by the absorption of CO_2 into the droplet. The contact liquid is coldest at the top of the tower, which determines how cold the flue gas becomes and thus the amount of CO_2 remaining in the flue gas. For example, a nominal 15% CO_2 stream attains 90% capture at temperatures slightly above −120°C and 99% CO_2 capture at approximately −135°C. After exiting the tower, the flue gas warms to its initial temperature by cooling the incoming streams in a countercurrent heat exchanger.

The captured CO_2 exits the bottom of the DHX as slurry of dissolved gas and suspended solid CO_2 in the contact liquid. This slurry passes through a pump, a heat exchanger that cools it back to the DHX injection temperature, and a solid–liquid barrier filter separator. This separator produces a clean contact liquid stream that recirculates to the DHX and a solid cake that enters the melter. The melter cools other portions of the process, as it melts the CO_2 to a liquid and then warms the CO_2 back to ambient temperature. Some of the contact liquid inevitably remains in this CO_2 stream until it passes through the distillation column purifier. The process produces CO_2 purities of up to >99.99%. Closed-loop refrigeration systems are combined with a multistream heat exchange to provide cooling, which is primarily used to cool the contact liquid after it warms in the DHX. This comparatively simple process converts flue gas from virtually any source into two streams: a light (or clean) gas at ambient pressure and pressurized liquid-phase CO_2 that can be adjusted to the specifications of essentially any CO_2 utilization market.

The nominal 1-ton (short ton) per day pilot plant version of the CCC process occupies three 20-foot shipping containers and has completed field and local tests in a broad range of industries, ambient conditions, and flue gas compositions. The results of these tests have recently been published (Frankman et al. 2021; Sayre et al. 2017). Figure 19.6 shows the results of a 200-hour test conducted as part of the collaboration between KAUST and Sustainable Energy Solutions, demonstrating

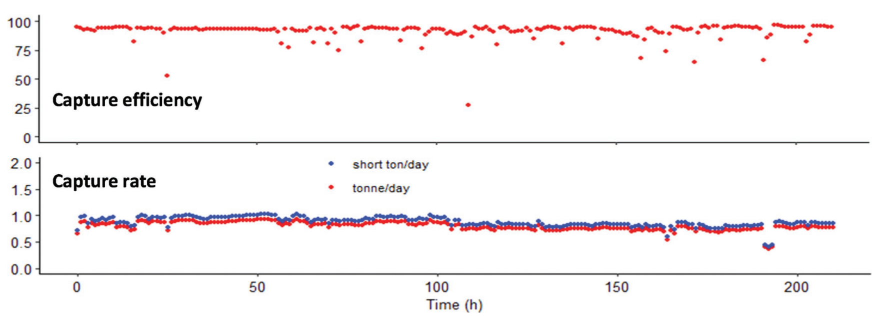

FIGURE 19.6 Results of the 200-hour test of the CCC system.

Source: Authors.

>90% capture efficiency at the 1 ton/day scale. The drops observed in efficiency occur during the defrosting process, which is intermittently activated in the system to avoid any accumulation of solid CO_2. Extensive testing of the system has led to process and equipment modifications that have improved reliability and performance.

A pilot plant of 1 ton per day was delivered to the Kingdom at the end of 2020. KAUST research staff were trained to operate the plant and they independently assessed the technology using CO_2 from high-pressure gas cylinders. Tests were also conducted using flue gas from combustion test rigs that burned diesel fuel. Figure 19.7 shows the skid located at KAUST. A successful demonstration of the

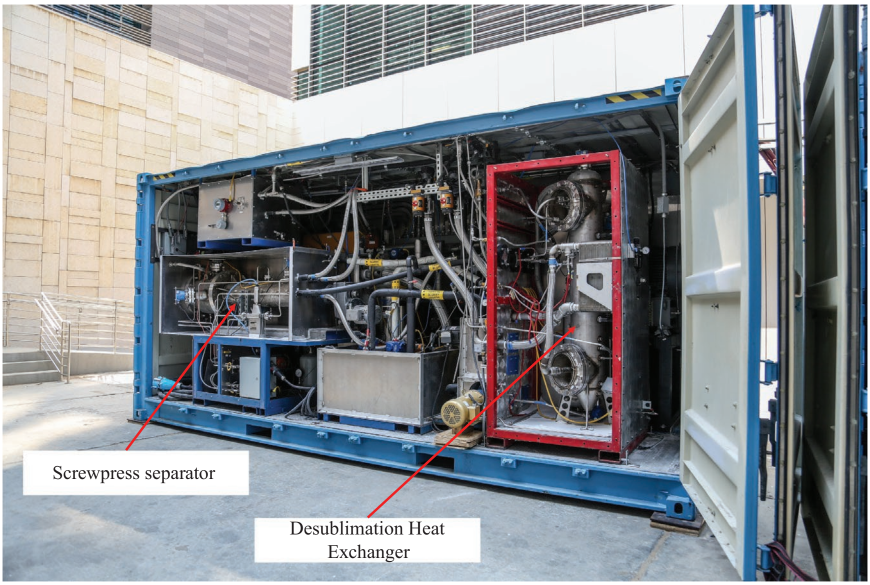

FIGURE 19.7 (a) CCC skid at KAUST and (b) Solid CO_2 separated in the screw press.

Source: Authors.

FIGURE 19.8 CCC skid demonstrations: left: Circular Carbon Initiative event in December 2020, right: Saudi Aramco visit with the Chief Technology Officer in March 2021.

Source: Authors.

skid was showcased at the Circular Carbon Initiative event hosted by KAUST in December 2020. Recently, a team of technologists from Saudi Aramco, led by their Chief Technology Officer Ahmed Al-Khowaiter, witnessed the demonstration of carbon capture at KAUST (Figure 19.8). The technology was also showcased to several delegates from Neom. These two organizations have shown both interest in the technology and willingness to support its adoption in Saudi Arabia.

Technoeconomics

A technoeconomic comparison of CCC with common amine-based technologies was recently presented at the Greenhouse Gas Control Technologies (GHGT) conference (Hoeger, Burt, and Baxter 2021). The National Energy Technology Laboratory (NETL) has also published a detailed report on technoeconomics performed for the benchmark cases of coal and natural gas power plants (Haslback et al. 2013). Two baseline studies were selected to evaluate the CCC technology: a 550-MW_e net supercritical pulverized coal power plant without carbon capture and an amine capture system that has the capacity to capture 90% of CO_2. The second system can capture approximately 13,000 tons of CO_2 per day at an approximately 13% mole fraction (wet basis) of CO_2 in flue gases. A typical commercial-scale SMR plant producing approximately 200 tons of hydrogen each day would require a carbon capture of 2,000 tons/day (almost six times smaller than the NETL benchmark case).

TABLE 19.3 Comparison of the CCC technology with amines for the NETL benchmark study

	Amines	*CCC*
Power needed (MJ_e/kg CO_2)	1.44	0.99
Parasitic load	27%	18%
Captured cost ($/ton CO_2)	42	27

Table 19.3 summarizes the system metrics used in the NETL benchmark study. It was found that CCC has an approximately 35% lower energy penalty and capture cost than the amine system.

SMR flue gases have higher concentrations of CO_2 than coal plant exhaust; hence, the specific energy penalty is expected to be approximately 10% lower for SMR than the value in Table 19.3 (Sustainable Energy Solutions 2019). Further, the capture cost is approximately 20% lower for the same scale when the CO_2 concentration rises from 13% to 20%. However, at a capture amount of only 2,000 tons/day, the capture cost per ton is almost double that of a coal system. As a result, the CO_2 capture cost for a typical SMR plant is $40–45/ton, which would add $0.36–0.40/kg to the cost of producing hydrogen (not including the CO_2 transportation and storage costs). Indeed, including these two costs would add another $10–15/ton based on NETL estimates (Haslback et al. 2013), which would raise the total cost of avoiding CO_2 to $50–60/ton. This amount is approximately 30% lower than the CO_2 avoidance cost reported for commercial-scale SMR by Collodi et al. (2017). The total cost contribution of CCS to the cost of hydrogen in this case would be approximately 0.5$/kg, making blue hydrogen economical and hence viable compared with green hydrogen in the near to mid-term.

Conclusion

The CO_2 emitted from a traditional hydrogen production SMR plant can be captured in multiple ways, with flue gas capture achieving the maximum CO_2 capture, potentially reducing the CO_2 footprint by 90%. Although Saudi Arabia is committed to reducing carbon emissions through its recently launched circular carbon economy campaign, decarbonizing its power industry using blue hydrogen requires a considerable scaling up of blue hydrogen and CCS facilities. Policy incentives and development efforts to reduce the costs of CCS are key drivers for achieving these goals. Multiple CCS technologies are available, some of which are mature, and others are under development. KAUST is developing CCC technology in collaboration with Sustainable Energy Solutions that has the potential to keep the additional cost of CCS under $0.5/kg of hydrogen and ensure that blue hydrogen is viable for large-scale deployment and adoption in the future.

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20

GEOLOGICAL HYDROGEN STORAGE

Hussein Hoteit and Abdulkader Afifi

Introduction

Saudi Arabia's command economy is based on hydrocarbons. Therefore, building sustainable growth in a low-emission economy is a major mission. Diversifying the economy, improving efficiency, and promoting renewable energy sources (solar, wind, and geothermal) are crucial imperatives for the Kingdom. However, fossil fuels are expected to remain the primary source of energy (Wogan, Carey, and Cooke 2019). The energy sectors in Saudi Arabia and worldwide must therefore adapt to stricter environmental regulations and carbon-constrained economies. Given the excessive carbon dioxide (CO_2) concentrations in the atmosphere, which are mostly attributed to the use of fossil fuels, Saudi Arabia has significant potential for carbon capture and storage in various underground formations (Hamieh et al. 2022, Vahrenkamp et al. 2021). Hence, storing gas underground (including both natural gas and hydrogen) and sequestering CO_2 are expected to be integral components of the energy mix (Figure 20.1).

The provision of reliable and cost-effective technology for the large-scale storage of hydrogen (whether blue or green) is crucial for a viable hydrogen-fueled economy. Blue hydrogen (combined via carbon capture and storage) is an environmentally friendly alternative to fossil fuels (Braun and Shabaneh 2021). Hydrogen storage, potentially on both the supplier and the consumer sides, represents a robust and adaptable energy system that compensates for the possible short-term imbalances between demand and supply and serves as a long-term strategic reserve (Bünger et al. 2016).

The energy industry has extensive experience with underground gas storage, including depleted hydrocarbon reservoirs (mostly gas), saline aquifers, and salt caverns. For instance, the storage capacity for natural gas in the United States is in the thousands of billion cubic feet range under standard conditions, as shown in

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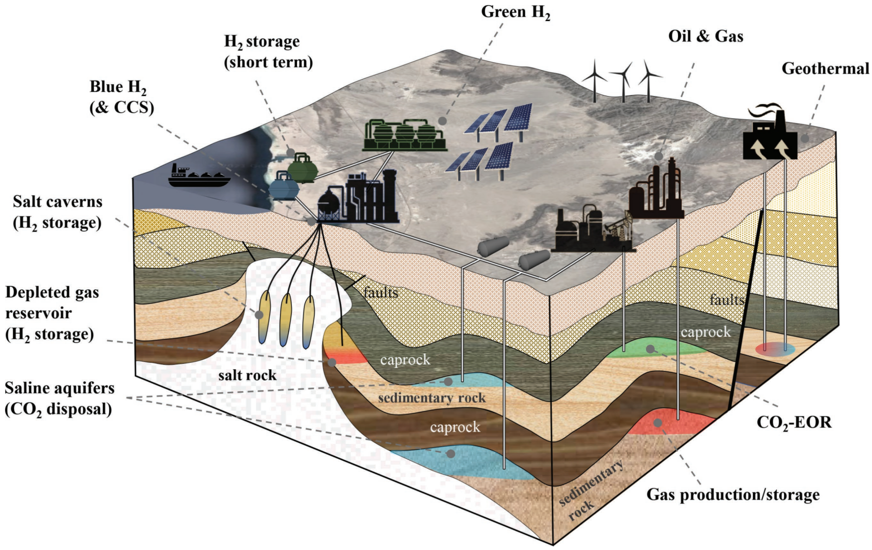

FIGURE 20.1 Role of underground gas storage and CO_2 sequestration in a balanced low-carbon energy mix, including hydrogen storage in salt caverns and depleted gas reservoirs.

Source: Authors.

TABLE 20.1 Storage capacities and number of storage fields in the United States

Type of underground storage	*Total capacity* (Bcf)*	*Working capacity (Bcf)*	*Withdrawal efficiency (%)*	*Number of fields*
Depleted reservoirs	7160	3930	59	328
Aquifers	1370	400	29	47
Salt caverns	700	480	68	37

Source: EIA (2019).

* Numbers rounded to the nearest 10.

Table 20.1 (EIA 2019). Depleted hydrocarbon reservoirs account for approximately 77% of this storage capacity, followed by aquifers (15%) and salt caverns (8%). The working gas capacity, which corresponds to total capacity minus cushion (unproduced) gas, accounts for approximately 50% of total storage capacity. Therefore, the working storage gas capacities of the depleted gas reservoirs, aquifers, and salt caverns are 82%, 8%, and 10%, respectively. The realized withdrawal efficiency (i.e., working capacity/total capacity) is the highest for salt caverns (68%) and lowest for aquifers (29%; Table 20.1). Salt caverns typically provide the highest gas withdrawal deliverability. A similar storage model is used in Europe, where the working storage gas capacities of depleted gas reservoirs, aquifers, and salt caverns are 65%, 25%, and 7%, respectively (UNECE 2013).

Similar to natural gas storage facilities, underground hydrogen storage (UHS) facilities (including salt caverns, depleted reservoirs, and saline aquifers) are scalable and cost-effective alternatives to physical- and chemical-based aboveground storage (Stolten and Emonts 2016). Aboveground hydrogen storage facilities have limited storage capacity (a few hours to a few days). These include gas storage in vessels and pipelines at a typical pressure range of 200–700 bar and liquid (cryogenic) hydrogen vessels at high pressure (approximately 350 bar; Klebanoff 2016). Providing large-scale energy supplies for weeks to months (within GWh) can be achieved by storing compressed hydrogen in underground reservoirs (Heinemann et al. 2021, Kruck et al. 2013). The potential advantages of UHS over aboveground storage include its higher storage capacity, low surface and environmental footprint, lower cost per stored volume unit, and superior safety conditions.

The underground storage of pure hydrogen has been limited to salt caverns in a few locations worldwide (Liebscher, Wackerl, and Streibel 2016). The feasibility of underground storage in porous rock formations remains unproven at a broad commercial scale. However, various R&D programs are focusing on improving this technology (HyChico 2021, SunStorage 2021). The storage mechanisms of hydrogen in porous media may not be significantly different from those of natural gas; therefore, the industry's rich experience in underground gas storage is relevant (Kruck et al. 2013). However, the thermodynamic properties of hydrogen and its biochemical affinity to interact with host rock formations and fluids raise additional technical challenges and operational costs. For instance, the mass density of hydrogen is approximately one order of magnitude lower than that of methane under similar temperature and pressure conditions. Thus, the storage capacity of hydrogen by mass in a given underground container is 10 times lower than that of methane under similar conditions. Moreover, the low viscosity of hydrogen and its potential reactivity with mineral formations, pore fluids, biosystems, and facility materials demand mitigation strategies. These strategies are not required for the underground storage of natural gas.

Hydrogen storage in salt caverns

Hydrogen can be efficiently stored in salt caverns because rock salt is nonporous and impermeable; therefore, fluids and hydrogen cannot infiltrate it. Salt caverns are an efficient storage option for hydrogen owing to their high-pressure confinement conditions. Caverns are constructed and shaped in salt domes via solution drilling, in which water is injected and recycled with an injection/production well (see Figure 20.1). The process produces large volumes of brine at the surface, which should be appropriately disposed. Salt caverns can provide superior injection/withdrawal deliverability than storage facilities in porous formations. In addition, less cushion (nonworking) gas is required, as shown in Table 20.1. However, the injection/production rates and corresponding variations in the stress field

TABLE 20.2 Summary of hydrogen storage projects in salt caverns

Storage project	*Depth range (m)*	*Volume (10^3 m^3)*	*Operating pres. (bar)*	*Energy (GWh)*	*Working gas (10^6 kg)*	*Withdrawal efficiency (%)*
Moss Bluff, United States	820–1400	566	55–152	123	3.7	62
Clemens Dome, United States	850–1150	580	70–135	81	2.4	47
Spindletop, United States	~1340	906	68–202	274	8.2	–
Teesside, United Kingdom	350–400	3×70	~46	26	0.76	–

Source: Caglayan et al. (2020); Liebscher, Wackerl, and Streibel (2016).

should be carefully managed to avoid compromising the structural integrity of the cavern (Bünger et al. 2016).

The few commercial-scale projects conducted for the underground storage of pure hydrogen are limited to salt caverns, including Moss Bluff, Clemens Dome, and Spindletop in the United States and Teesside in the United Kingdom. Table 20.2 presents the storage capacities and characteristics of these four projects (Caglayan et al. 2020, Liebscher, Wackerl, and Streibel 2016). Storing hydrogen in salt caverns requires the following conditions:

1 Geology: The presence of salt bodies in the subsurface with suitable depth, shape, and size (thickness and width) located near the hydrogen production/consumption sites.
2 Site development: This involves the construction of the cavern, salt disposal, a storage scheme with either cushion gas or brine injection, surface facilities, and transportation.
3 Storage management: This involves the safe and optimized management of the pressure range, injection/withdrawal rates, amount of cushion gas (if used), economics of hydrogen compression, operational pressures, and monitoring for safe hydrogen containment.

Hydrogen storage in porous media

Hydrogen storage in sedimentary reservoirs has not yet been performed at an industrial scale. Despite the vast experience and know-how regarding the storage of compressed air, natural gas, and town gas in porous formations, storing hydrogen poses additional technical challenges. Town gas, which is a product of coal gasification, contains approximately 50% free hydrogen and the remainder is a mixture of methane, carbon monoxide, and other gases (Kruck et al. 2013). The storage and use of this gas have mostly been discontinued.

Storage capacity

The main requisites for UHS in porous formations include the three essential elements of a reservoir: the trap, seal, and accessible reservoir rock (Selley and Sonnenberg 2014, Stolten and Emonts 2016). Geological traps are structural (e.g., anticlines), diapiric, stratigraphic, or other 3D geometric structures that provide a confined pore volume that maintains fluids in place within the trap and spill points (see Figure 20.2). The seal (e.g., shale and evaporite formations) is an impermeable caprock that covers the trap. It should exhibit low hydraulic conductivity; be sufficiently thick to maintain its mechanical integrity; and restrict the vertical migration of the injected fluid from the reservoir based on diffusion, buoyancy, capillary, and viscous forces. The reservoir rock is a sedimentary sandstone or carbonate formation with sufficient effective porosity $\left(\phi > 15\%\right)$, low irreducible water saturation $\left(S_{wir} < 0.2\right)$, high permeability $\left(k > 1000mD\right)$ for gas mobility and deliverability, and low heterogeneity for improved storage efficiency, as reflected by a high net-to-gross ratio.

To store gas, a depleted hydrocarbon (gas or oil) reservoir with a strong water drive is treated as a water-saturated saline aquifer owing to the substantial water volumes that have invaded the reservoir to replace the volumes of extracted hydrocarbons. A similar concept is applied to water-flooded reservoirs. In this context, it is important to emphasize that depleted gas reservoirs are referred to as non-associated gas reservoirs with an absent or insignificant water drive. In such reservoirs, water saturation remains almost unchanged after reservoir depletion. As no external water invades the reservoir, the resulting depletion pressure is much lower than the initial reservoir pressure.

In underground gas storage, a certain proportion of the stored volume (i.e., cushion gas) is left in the reservoir to maintain a minimum pore pressure for economic and safety reasons. The withdrawal gas rate is proportional to the difference between the reservoir bottom-hole pressure and wellhead pressure. In closed reservoirs (e.g., depleted gas reservoirs), the withdrawal rate declines as the reservoir pressure decreases during depletion. Consequently, the withdrawal rate is often maintained above an economic limit by preventing the reservoir pressure from dropping below a threshold. Rock compaction, subsidence, and caprock integrity also limit the storage turnover frequency and minimum/maximum pore pressures associated with the withdrawal/injection rates and depletion/filling limits of the reservoir.

In open reservoirs with a strong water drive, the reservoir pressure does not decrease with depletion, which helps maintain high well deliverability. Nevertheless, cushion gas must still be used as a buffer to prevent advancing water from reaching the well at high cuts, which could cause operational complications. Moreover, the consecutive retrieving–advancing (i.e., drainage–imbibition) waterfront

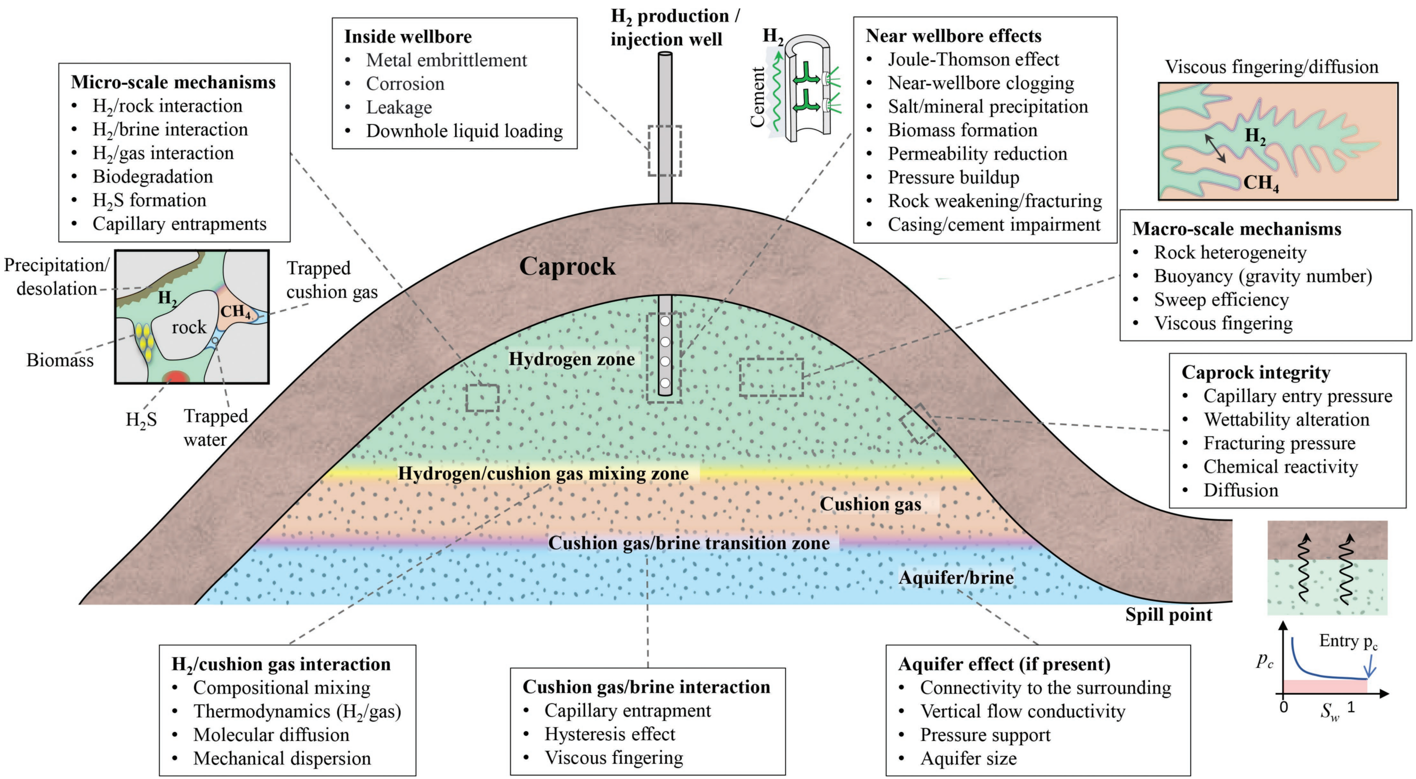

FIGURE 20.2 Different bio-chemo-hydro-thermo-mechanical mechanisms relevant for hydrogen storage in porous media (e.g., depleted gas reservoirs and aquifers) at different temporal and spatial scales.

Source: Authors.

movement encountered during the injection/withdrawal process induces pore-scale discontinuities in the gas phase. This phenomenon leads to the cumulative capillary entrapment of the cushion gas (i.e., the hysteresis effect; Lake 1989). The percentage of cushion gas used in saline aquifers is typically higher than that required for depleted gas reservoirs (Table 20.1). For instance, the cushion gas percentage can be two-thirds of the total gas capacity in saline aquifers, thereby leaving only one-third of the producible gas (i.e., working gas; (Kruck et al. 2013).

The volume capacity $\left(V_{H_2,sc}\right)$ of the working hydrogen gas under standard temperature and pressure conditions (i.e., T = 15.5°C and p = 1 bar) is estimated as follows:

$$V_{H_2,sc} = V_b.\phi.N_{tG}.\left(1 - S_w\right).\left(1 - F_{cg}\right).E_g \tag{1}$$

where,

$V_{H_2,sc}$: volume of hydrogen gas under standard conditions (sc) $\left[L_{sc}^3\right]$

V_b: bulk volume of the trap under reservoir (res) and conditions $\left[L_{res}^3\right]$

ϕ: average effective porosity [−]

N_{tG} : average net-to-gross ratio [−],

S_w : average water saturation [−]

F_{cg} : cushion gas (cg) volume fraction [-], which is the ratio of the cushion gas volume to the total gas volume (i.e., the cushion gas plus working gas volumes) under reservoir conditions. F_{cg} is an important storage efficiency factor that reflects the pore volume occupied by the cushion gas relative to the total pore volume available for gas storage in the reservoir at a given time. The typical range of F_{cg} is 0.2 (high efficiency) to 0.7 (low efficiency) depending on the reservoir type and conditions.

E_g: hydrogen gas expansion factor $\left[L_{sc}^3 / L_{res}^3\right]$, which is defined as the ratio of the hydrogen gas volume under standard conditions to the hydrogen gas volume under reservoir conditions.

The mass $\left(M_{H_2}\right)$ of the hydrogen working gas at a given time is calculated as follows:

$$M_{H_2} = V_b.\phi.N_{tG}.\left(1 - S_w\right).\left(1 - F_{cg}\right).\rho_{H_2,res} \tag{2}$$

or simply with Eq. (1): $M_{H_2} = V_{H_2,sc}.\rho_{H_2,sc}$, where $\rho_{H_2,res}$ and $\rho_{H_2,sc}$ are the densities under reservoir and standard conditions, respectively.

Storage mechanisms

Underground reservoirs in sedimentary formations (particularly depleted gas reservoirs) and, to a lesser extent, saline aquifers and depleted oil reservoirs can provide sufficient large-scale storage capacity when salt caverns are unavailable. The management of reservoir storage, including gas injection, storage, and withdrawal from porous rock formations, involves the optimization of multiple design- and time-dependent operational parameters. Such parameters are related to the numbers and types of wells and operating pressure and rate constraints, which should be managed under different static and dynamic subsurface uncertainties. Figure 20.2 illustrates the main mechanisms of the bio-chemo-hydro-thermo-mechanical nature, which can be relevant at different temporal and spatial scales. Such mechanisms are more or less significant depending on the reservoir type and conditions.

Many of the fundamental storage aspects highlighted in Figure 20.2 (e.g., multiphase flow, mixing and trapping, rock/fluid interactions, caprock integrity, flow assurance, and risk of leakage) have common backgrounds with the better-known stored methane, CO_2, and town gas volumes in porous rock formations. Nevertheless, hydrogen gas exhibits distinct thermodynamic and biochemical characteristics that may change the ranking of storage mechanisms in terms of relevance and significance. Some of the main properties of hydrogen are reviewed, and comparisons with methane are provided as references in the following sections.

Hydrogen density and viscosity

The thermodynamic properties of hydrogen are key parameters that directly affect storage dynamics and efficiency. Figure 20.3 shows the calculated density and viscosity variations of hydrogen as a function of temperature (15–135°C) and pressure (1–350 bar), representing the typical conditions encountered during the storage process. The plotted properties were calculated from the NIST Chemistry WebBook based on different equations of states with reasonable accuracy (within ±0.1% for density and ±15% for viscosity; Lemmon et al. 2021).

Hydrogen behaves differently than methane does. For instance, the density of hydrogen is approximately one order of magnitude lower than that of methane under identical conditions, as shown in the log–log plot in Figure 20.4a, and the former has a slightly lower gas expansion factor (Figure 20.4b). This implies that the storage capacity by volume of hydrogen in a reservoir is marginally less than that of methane and that by mass is 10 times lower. This consequently indicates lower energy storage efficiency overall. The dynamic viscosity of hydrogen shows a weaker dependency on temperature and pressure; it is approximately 1.5–2 times lower than the viscosity of methane, as shown in Figure 20.4. The lower viscosity of hydrogen provides better deliverability for a given pressure drawdown. However, the low viscosity of hydrogen may induce unstable hydrogen/methane or hydrogen/water displacement fronts (i.e., viscous fingering) and a potentially higher risk of leakage, as

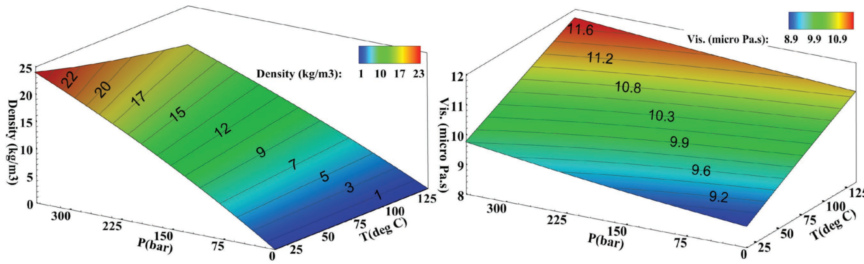

FIGURE 20.3 Density (left) and viscosity (right) of pure hydrogen versus temperature (15–135°C) and pressure (1–350 bar).

Source: Authors, calculated from the NIST Chemistry WebBook (Lemmon, McLinden, and Friend 2021).

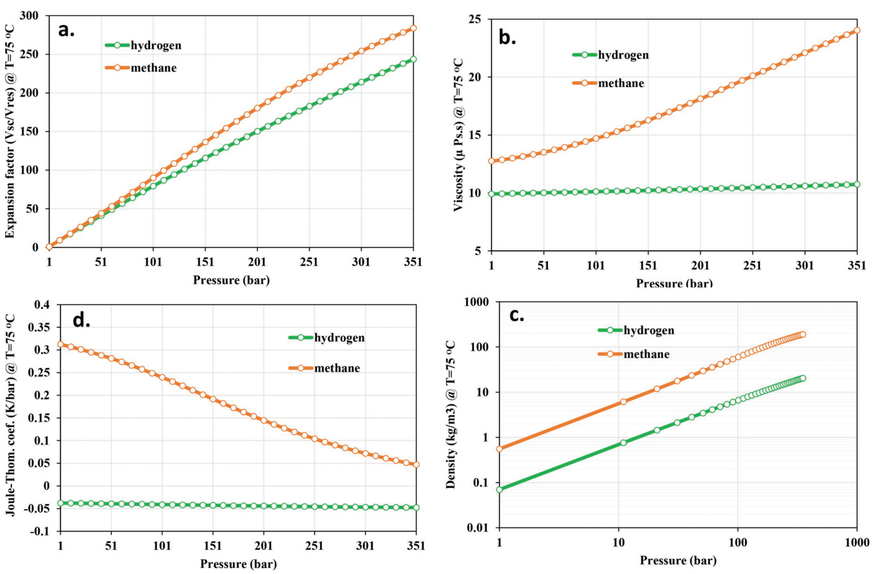

FIGURE 20.4 Density (a), expansion factor (b), viscosity (c), and Joule–Thomson coefficient (d) of hydrogen and methane versus pressure at $T = 75°C$.

Source: Authors, calculated from the NIST Chemistry WebBook (Lemmon, McLinden, and Friend 2021).

discussed in the next section. Viscous fingering is a phenomenon that occurs when a low-viscosity fluid displaces a highly viscous fluid, thereby leading to an uneven displacement front. This phenomenon results in a lower sweep efficiency and possibly a larger hydrogen/methane mixing zone owing to diffusion (see Figure 20.2). The hydrogen/methane mixture can establish a smooth viscosity gradient between the working gas (hydrogen) and cushion gas (methane), which improves the stability of the displacement fronts and prevents further mixing. Therefore, retaining the mixing zone as part of the cushion gas is beneficial for the production process.

Hydrogen Joule–Thomson effect

Unlike most gases (including methane), hydrogen exhibits a negative Joule–Thomson coefficient (Figure 20.4d) in typical temperature and pressure-operating ranges. The Joule–Thomson coefficient $\left(\mu_{JT}\right)$, which reflects the nonideal characteristics of the gas, is the rate of change in the temperature with changing pressure at a constant enthalpy H:

$$\mu_{JT} = \left(\partial p \big/ \partial T \right)_H \tag{3}$$

The Joule–Thomson coefficient varies with temperature and pressure and becomes negative when the change in pressure $\left(\partial p\right)$ has the opposite sign to the change in temperature $\left(\partial T\right)$. A negative μ_{JT} implies that hydrogen increases temperature with decreasing pressure (i.e., gas expansion) and decreases temperature with increasing pressure (i.e., gas compression). This trend is the opposite to that observed for methane and CO_2. For instance, the Joule–Thomson effect during CO_2 injection may cause cooling, leading to hydrate or ice formation (Hoteit, Fahs, and Soltanian 2019). However, when hydrogen is injected into a reservoir, the gas expands at the well bottom hole across the perforations, resembling a throttling effect. This mechanism may cause a localized increase in temperature near the wellbore and surrounding zone depending on the range of the pressure drop and duration of the injection. The opposite thermal effect (i.e., cooling) may occur during production; however, it is less significant, as the pressure drop between the reservoir and wellbore occurs over a larger radial distance. The resulting cooling effect is not localized and therefore cannot alter the reservoir temperature.

Hydrogen–water solubility

Unlike CO_2, the solubility of hydrogen in brine is relatively low. For instance, at $p = 100$ bar, $T = 75°C$, and salinity = 1 mol (approximately 60,000 ppm), the mass fraction of hydrogen () in brine is the order of 10^{-4} (Chabab et al. 2020). Within such a small solubility range, the fraction of the total hydrogen mass that can be lost owing to solubility in a reservoir with an irreducible brine saturation of 20% is less than 0.4%, which is insignificant. By contrast, the calculated mass fraction of water that evaporated into the gaseous hydrogen phase () under the conditions mentioned above is approximately $y_{H_2O} = 0.03$ (Chabab et al. 2020). With such an evaporation rate, flooding the pore space of the rock with a few thousand hydrogen pore volumes may result in the total evaporation of water. This phenomenon can occur near the wellbore during gas withdrawal, leading to salt precipitation (salting out) and potential clogging. This salting-out phenomenon has been experienced during CO_2 storage in saline aquifers, where salt precipitation occurs within the wellbore owing to the flowback and evaporation of formation water (Talman et al. 2020).

Furthermore, the presence of water vapor in the produced hydrogen gas triggers other operational implications, such as the need for hydrogen purifying and drying to prevent facility corrosion (Stolten and Emonts 2016).

Caprock sealing capacity

Capillary flow mechanisms corresponding to multiphase hydrogen/brine systems play a dominant role in determining the mobility, distribution, and entrapment of hydrogen in the reservoir as well as the risk of leakage into the caprock (Ali et al. 2022a, 2022b, Heinemann et al. 2021). Capillary mechanisms are quantified by the relative permeability of water, hydrogen, and rock as well as the capillary pressure curves, which can be measured in core flood experiments. However, such measurement results for hydrogen are scarce in the literature. Other indirect methods involve correlations or pore-scale modeling based on interfacial tension and contact angle measurements (Ali et al. 2021, Hashemi et al. 2021, Iglauer, Ali, and Keshavarz 2021, Yekta et al. 2018).

The leakage mass flux of hydrogen $\left(q_{H_2}\right)$ through the caprock is composed of advection flux ($q_{H_2}^{adv}$; driven by capillary and viscous forces through the gaseous phase) and diffusion flux ($q_{H_2}^{diff}$; driven by the diffusion of hydrogen through the aqueous phase, i.e., $q_{H_2} = q_{H_2}^{adv} + q_{H_2}^{diff}$; Espinoza and Santamarina 2017). The diffusion process occurs in the aqueous phase and can be approximated using Fick's law. The Fickian flux is proportional to the hydrogen concentration gradient across the caprock within the aqueous phase. Consequently, its value is expected to be negligible owing to the low solubility of hydrogen in brine. The advection flux across the caprock can be estimated using Darcy's law:

$$q_{H_2}^{adv} = \rho_{H_2} \frac{kk_r}{\mu_{H_2}} \left(\frac{\Delta p - \rho_{H_2} g h_{cap}}{h_{cap}} \right) \tag{4}$$

where h_{cap} denotes the thickness of the caprock. Eq. 4 is only valid in the presence of a continuous hydrogen gaseous phase across the caprock, which is initially absent.

The hydrogen/water capillary pressure is the difference between the nonwetting and wetting phase pressures: $p_c = p_{H_2} - p_w$. Hydrogen gas (i.e., a nonwetting phase) cannot invade the caprock until the pressure drop exceeds a certain threshold, which is known as the capillary entry pressure, p_c^*. The capillary entry pressure can be approximated with the Laplace equation, hydrogen/water interfacial tension σ_{H_2}, and wetting contact angle θ_{H_2}:

$$p_c^* = \frac{2\sigma_{H_2} \cos\theta_{H_2}}{\tilde{r}} \tag{5}$$

where $\tilde{r}$ represents the effective pore throat radius of the caprock formation.

According to an analogy with CO_2 storage in aquifers, the sealing capacity of the caprock, which is quantified by the *sealing number*, is the ratio of the capillary entry pressure to the pressure difference (Δp) across the caprock (see Figure 20.5a). In connected aquifers (but not depleted reservoirs), the buoyancy pressure is $\Delta p = \Delta p_{buoy} = g\,\tilde{h}_{H_2}\left(\rho_w - \rho_{H_2}\right)$; therefore, the sealing number relative to hydrogen, π_{1,H_2}, can be expressed as follows [modified from (Espinoza and Santamarina 2017)]:

$$\pi_{1,H_2} = \frac{p_c^*}{\Delta p} = \frac{2\sigma_{H_2}\cos\theta_{H_2}}{\tilde{r}\,g\,\tilde{h}_{H_2}\left(\rho_w - \rho_{H_2}\right)} \approx \frac{2\sigma_{H_2}\cos\theta_{H_2}}{\tilde{r}\,g\,\tilde{h}_{H_2}\rho_w} \quad (6)$$

In Eq. (6), g is the gravitational acceleration and $\tilde{h}_{H_2} = h_{H_2} + h_{H_2}^{eq}$ is the height of the hydrogen gas column () plus the height of the cushion gas column, which is represented by the equivalent hydrogen height $h_{cg}^{eq} = \left(\rho_{cg}/\rho_{H_2}\right)h_{cg}$. When $\pi_{1,H_2} >> 1$, the gas phase experiences capillary holdup (i.e., entrapment). When $\pi_{1,H_2} << 1$, the buoyancy pressure exceeds the capillary entry pressure, thereby allowing hydrogen to invade the caprock.

The hydrostatic trapping equilibrium (i.e., $\pi_{1,H_2} = 1$) provides the maximum stable storage column for hydrogen:

$$\tilde{h}_{H_2}^{max} = \frac{2\sigma_{H_2}\cos\theta_{H_2}}{\tilde{r}\,g\left(\rho_w - \rho_{H_2}\right)} \quad (7)$$

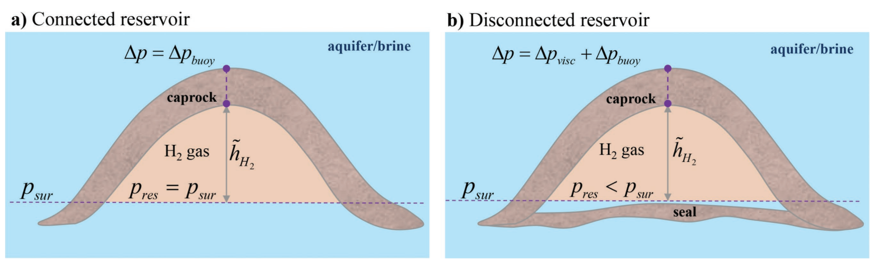

FIGURE 20.5 Illustrations of a connected saline aquifer under hydrostatic equilibrium conditions (a) and a disconnected depleted gas reservoir in which the reservoir pressure p_{res} is lower than the surrounding pressure p_{sur} at the same depth (b).

Source: Authors.

According to a comparison of Eq. (7) with the maximum stable column for methane $\tilde{h}_{C_1}^{\max}$:

$$\frac{\tilde{h}_{H_2}^{\max}}{\tilde{h}_{C_1}^{\max}} = \left(\frac{\sigma_{H_2}\cos\theta_{H_2}}{\sigma_{C_1}\cos\theta_{C_1}}\right)\frac{\left(\rho_w - \rho_{C_1}\right)}{\left(\rho_w - \rho_{H_2}\right)} \approx 0.95\left(\frac{\sigma_{H_2}\cos\theta_{H_2}}{\sigma_{C_1}\cos\theta_{C_1}}\right)_{@\,p=100bar} \tag{8}$$

Eq. 8 shows that wettability (i.e., interfacial tension and contact angles) influences the storage capacity (height) of hydrogen compared with methane storage. As previously discussed, hydrogen density is approximately 10 times smaller than that of methane. Nevertheless, both gas densities are smaller than those of water. Therefore, the relatively low density of hydrogen does not significantly reduce the allowed storage height compared with that of methane. For instance, at p = 100 bar, the contribution of the density difference is only a 5% reduction in the maximum height compared with that of methane. At higher pressures, the effect becomes more pronounced, reaching up to 20% at p = 350 bar.

Two important observations about the sealing capacity are noteworthy. First, in depleted gas reservoirs, the height of the gas column is constant and independent of the reservoir pressure. This behavior is different from that of open saline aquifers in which the gas column height increases with reservoir filling as the gas displaces the aquifer downward. Due to hydrostatic nonequilibrium in depleted reservoirs, the pressure difference in Eq. 6 becomes $\Delta p = \Delta p_{visc} + \Delta p_{buoy}$, where $\Delta p_{visc} = p_{res} - p_{sur}$ is due to the nonequilibrium conditions that cause an additional driving viscous force (see Figure 20.5b). is zero for open reservoirs and negative for depleted reservoirs, as is often kept below the surrounding hydrostatic pressure p_{sur}. At negative Δp_{visc} (Δp is smaller), the sealing number in Eq. 6 rises, indicating more stable capillary-trapping conditions. Under high depletion conditions, Δp can become negative, which induces a driving force across the seal in the opposite direction (i.e., from the surrounding aquifer into the reservoir). In this scenario, hydrogen leakage may not be a concern. However, an elevated pressure difference (Δp; positive or negative) between the reservoir and surrounding formation may deteriorate the mechanical stability of the seal, as discussed later.

Second, violating the hydrostatic trapping equilibrium condition (i.e., $\pi_{1,H_2} < 1$) does not imply the immediate leakage of hydrogen through the caprock. This simply means that the capillary flow barrier is bypassed by the gas; however, the gas must still propagate through the tight seal while displacing the in-situ water via a co-current or counter-current flow. This leakage process is slow without the chemical or mechanical deterioration of the caprock. The advective leakage velocity of hydrogen is decreased by the low absolute and relative permeabilities of the caprock and increased by the high-pressure buildup and low viscosity of hydrogen.

Mechanical stability and pore pressure

Another important aspect of gas storage is the retention of the mechanical stability of the seal and near-wellbore formation. Gas injection locally increases the pore pressure around the perforated interval of the well, which is followed by pressure diffusivity and pressure buildup in the reservoir. The local and regional increases in pore pressure alter the stress field equilibrium. Under extreme conditions, overinjection can cause irreversible mechanical failure in rock formations. For example, it can create hydraulic fractures or activate existing faults and fractures, which degrade reservoir containment ability (Espinoza, Kim, and Santamarina 2011, Niemi, Bear, and Bensabat 2017, Zoback 2007). Therefore, monitoring and controlling the injection pressure near the wellbore and pressure buildup at the caprock are crucial for safe storage (Espinoza and Santamarina 2017).

During gas filling, the pressure at the injection well (i.e., bottom-hole pressure) is a function of the gas conductivity in the reservoir and volumetric injection rate under reservoir conditions. For a given surface volumetric rate, the realized volumetric rate at the bottom hole varies as a function of the gas compressibility under reservoir conditions. Hydrogen has a lower viscosity than methane (see Figure 20.4a), which provides it with higher mobility and therefore faster pressure dissipation. By contrast, it exhibits a lower expansion factor (Figure 20.4b), which leads to a lower injection efficiency than that of methane. In other words, for the same injected volume of methane and hydrogen under surface conditions, hydrogen occupies a larger volume under reservoir conditions, resulting in higher injection pressure.

We use simulations to assess the two competing mechanisms of hydrogen (i.e., compressibility and mobility) and their effects on injectivity and pressure buildup. Two scenarios (i.e., the injection of methane and hydrogen into a synthetic heterogeneous saline aquifer representing a four-way anticline closure; see Figure 20.6) are simulated. The reservoir is initially brine-saturated at an initial, T = 75°C and p = 120 bar. One vertical well is used for gas injection, which is perforated away from the crest to prevent the over-pressurization of the caprock neighborhood. Figures 20.6a and 20.6b present the gas saturation profiles for methane and hydrogen at different times, respectively.

The saturation conditions during the gas filling period corresponding to the dimensionless times t = 0.05, 0.15, 0.35, and 1.0 are plotted; the surface volumetric injection rates are identical in both scenarios. At t = 0.35, the injection stops and the simulation continues to track the movement of the fluids and pressure behavior. During injection, the simulation results show similar overall characteristics for methane and hydrogen. In both cases, gas percolates through the water-saturated medium toward the top of the structure. However, hydrogen shows slightly higher dissipation and fingering levels, which result in lower filling efficiency owing to its adverse mobility ratio relative to water. After the shut-in of the injection well, the pressure and two-phase system are not in the hydrostatic equilibrium.

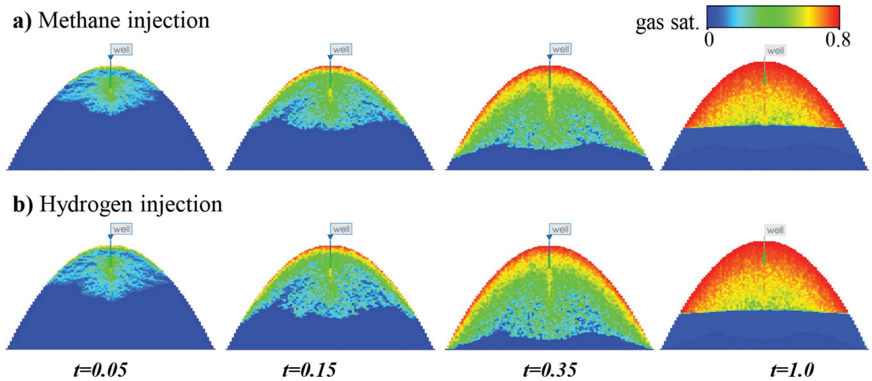

FIGURE 20.6 Vertical cross-sections of simulated gas storage in a heterogeneous saline aquifer: (a) methane and (b) hydrogen at different dimensionless times; in each case, the gas is injected until $t = 0.35$, followed by a shut-in to the injection well until $t = 1$. Vertical exaggeration of the cross-section: 5:1.

Source: Authors.

As a result, the gas (hydrogen or methane) and water phases continue to flow, where the slow mobile water continues to drain downward. By contrast, the advanced gas into the aquifer retrieves backward, leaving behind a capillary-trapped gas of saturation in the range of 5% below the established gas–water contact (see Figure 20.6, $t = 1.0$).

The flow characteristics of the two gases are not substantially different. However, a greater increase in pressure is obtained with hydrogen than with methane. Figure 20.7a shows the calculated increases in pressure for the two gases at the top and bottom of the reservoir. The increase in pressure is plotted as the ratio of the transient (time-dependent) pressure to the initial pressure. At identical volumetric surface rates, hydrogen injection results in higher pressure despite its higher mobility than that of methane. This behavior can be explained by analyzing the well injectivity indices of hydrogen $\left(WI_{H_2}\right)$ and methane $\left(WI_{C_1}\right)$. This index represents the surface volumetric rate that can be achieved at a unit of injection pressure. The plotted ratio $\left(WI_{H_2}/WI_{C_1}\right)$ in Figure 20.7b shows lower injection efficiency for hydrogen than for methane, which is the result of the lower expansion factor of hydrogen. However, when the volumetric rates of reservoir conditions are applied, hydrogen shows higher injection efficiency than methane (Figure 20.7b), which is a result of the higher mobility of hydrogen. In conclusion, hydrogen exhibits lower injection and storage efficiencies than methane. Other possible challenges for hydrogen storage regarding the chemical interaction with rocks and stimulation of microbes are beyond the scope of this chapter and are discussed elsewhere (Heinemann et al. 2021).

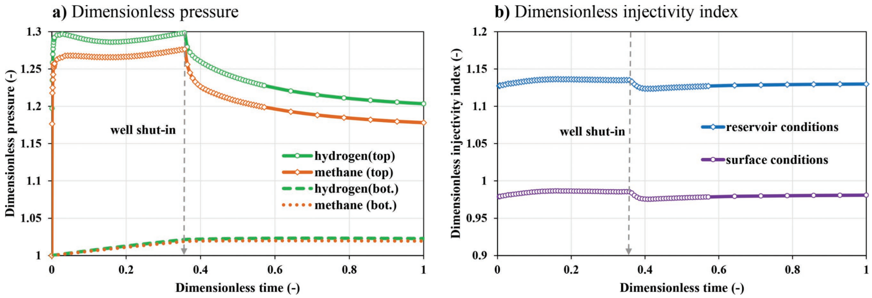

FIGURE 20.7 (a) Dimensionless pressures of hydrogen showing higher increases at the top and bottom of the reservoir than methane, and (b) ratio of the well injectivity index of hydrogen compared with that of methane based on the surface and reservoir volumetric rates.

Source: Authors.

Potential for hydrogen storage in Saudi Arabia

The Kingdom of Saudi Arabia includes most of the Arabian Peninsula and straddles three geological provinces: (1) the Arabian Shield in the center, which is flanked by two sedimentary basins; (2) the Arabian platform to the east; and (3) the Red Sea Basin to the west (Figure 20.8). The basement rocks exposed in the Arabian Shield consist of Precambrian metamorphic rocks and igneous intrusions such as granite. As these rocks are crystalline, dense, and nonporous, they cannot contain any fluid, except minute amounts within fractures.

The two sedimentary basins in which the basement is buried under layers of sedimentary rocks that are 10 km thick in some areas show potential for UHS. These rocks include porous layers of sandstone and limestone, which are generally water-saturated aquifers. The shallow groundwater aquifers are relatively fresh or brackish, whereas the deeper aquifers are saline brine. Some of the sandstone and limestone layers are also filled with hydrocarbons in the oil and gas reservoirs, particularly in the eastern province (Figure 20.8).

The sedimentary basins also contain layers of evaporitic rocks composed of anhydrite ($CaSO_4$) and/or halite (NaCl). The rapid recrystallization of these minerals during burial and deformation renders them ductile, nonporous, and impermeable to fluids (Tarkowski and Czapowski 2018). Rock salt is particularly suited for hydrogen storage because it forms salt diapirs of different sizes and shapes. These diapirs rise from the salt layer to shallower depths, sometimes reaching the surface, and their vertical dimensions far exceed the original thickness of the salt layer. For example, the heights of some salt diapirs in the Red Sea exceed 3,000 m above the base of the salt layer.

Solution caverns in salt are the tightest option for UHS (Lord, Kobos, and Borns 2014, Tarkowski, Uliasz-Misiak, and Tarkowski 2021). Several conditions must

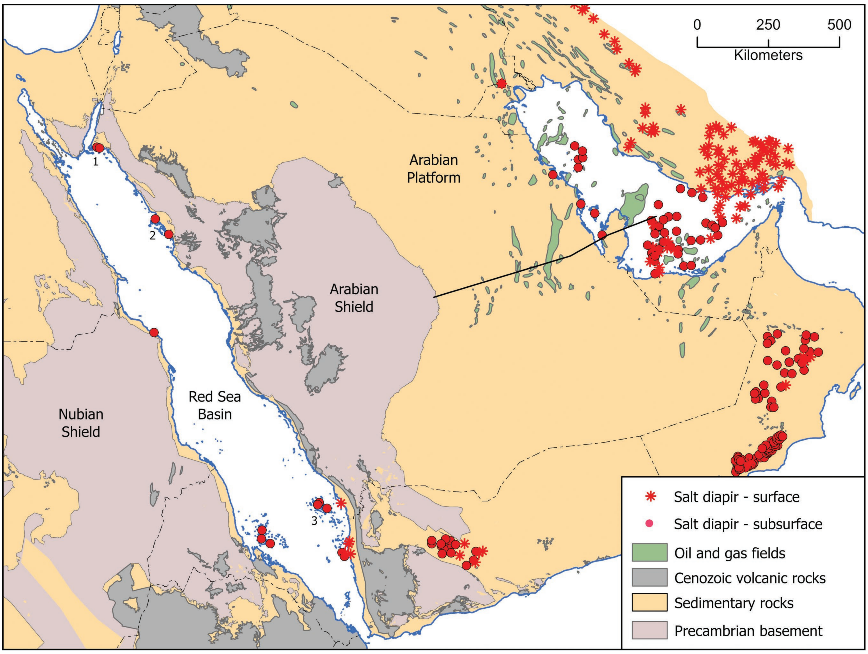

FIGURE 20.8 Generalized geological map of the Arabian Peninsula showing the location of surface and subsurface salt diapirs. The numbers indicate shallow salt diapirs in (a) the Midyan basin, (b) Umm Luj basin, and (c) Farasan Islands, which have potential for hydrogen storage.

Source: Authors.

be met for practical hydrogen storage in salt diapirs, the top of which should be located at a relatively shallow depth (100–1,000 m) below the surface because greater depths result in higher pressure, cavern instability, and higher costs. The depths, shapes, and sizes of salt diapirs in the subsurface are illuminated by reflection seismic surveys, particularly 3D surveys, acquired for hydrocarbon exploration. The salt should be pure and free of foreign rock inclusions that accumulate in the sump at the bottom of the solution cavern. Foreign rock inclusions in salt reduce the cavern volume and may react with hydrogen to form H_2S and/or methane.

Red Sea Basin

Seismic and well data acquired for hydrocarbon exploration reveal that most of the Red Sea Basin is underlain by a postrift Middle Miocene salt of the Mansiyah Formation (Hughes and Johnson 2005). The salt extends partly under the coastal plain, and its thickness is highly variable owing to salt tectonics (Heaton et al. 1995, Tubbs et al. 2014). The salt is highly tectonized by ductile flow and it forms hundreds of salt structures such as rollers, pillows, diapirs, and allochthonous

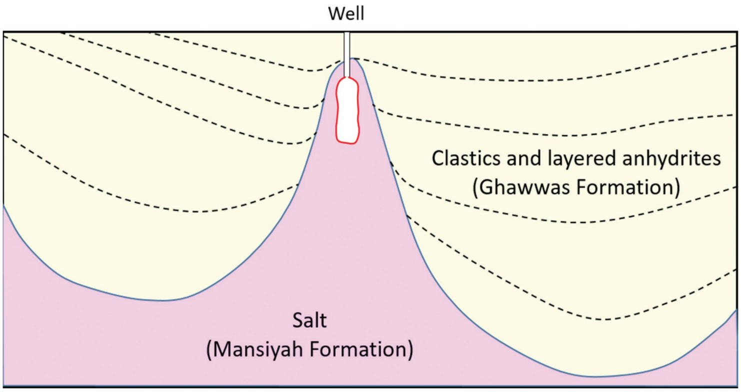

FIGURE 20.9 Schematic cross-section of a typical salt diapir along the Red Sea coast. The Middle Miocene salt has risen through a 3-km thick synkinematic overburden of Late Miocene clastics and layered anhydrite. A cylindrical solution cavern is shown schematically at the top of the diapir; it is formed by a single vertical well that also serves for injection and production.

Source: Authors.

canopies. The vast majority of these structures are located offshore, where UHS is impractical owing to the deep water and high cost. Nevertheless, there are several shallow onshore diapirs (domes), the tops of which are shallower than 500 m below the surface. These are potential sites for hydrogen storage (Figure 20.8). The lateral dimensions of each diapir are sufficient to accommodate several cylindrical solution caverns leached from vertical wells (Figure 20.9). Two shallow diapirs are located in the Midyan Basin (site 1 in Figure 20.8) at the site of the Neom development project and two diapirs are located in the Umm Lujj Basin (site 2 in Figure 20.8) at the Red Sea Development project site. The Farasan Islands (site 3 in Figure 20.8) are also suitable for UHS because some are underlain at very shallow depths (<100 m) by thick salt canopies. In addition, salt diapirs have breached the surface in Jizan in Saudi Arabia and Jabal Al Milh in Yemen (Bosence et al. 1998); salt had been mined at both locations until recently (Figure 20.8). In some areas, Mansiyah salt diapirs contain dismembered anhydrite and shale impurities, which may react with hydrogen to form H_2S and methane, and this should be carefully studied when evaluating long-term hydrogen storage (Laban 2020).

Arabian platform

The northern, central, and eastern provinces of Saudi Arabia are underlain by a Phanerozoic sedimentary basin that deepens toward the east, reaching a thickness of >8 km under the Arabian Gulf (Figure 20.10). Paleozoic sedimentary rocks are predominantly clastic (sandstones and shales), whereas Mesozoic and Cenozoic rocks are predominantly platform carbonates and anhydrite (Sharland et al. 2001).

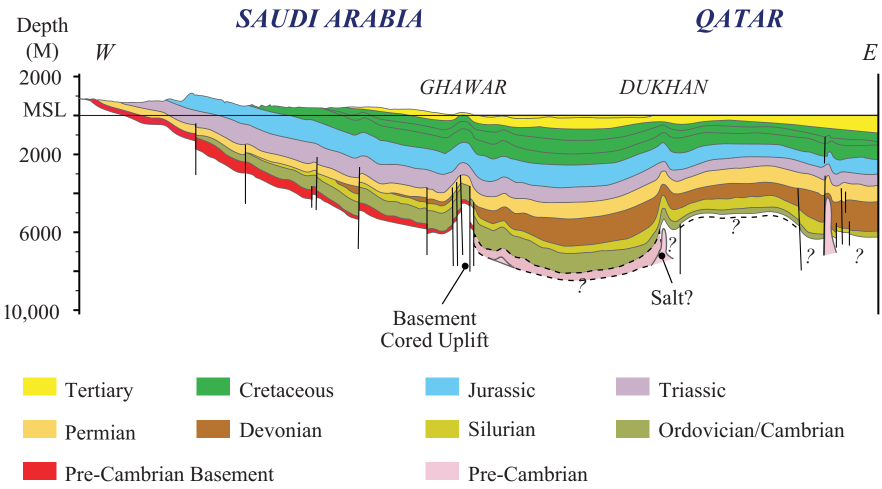

FIGURE 20.10 Regional E-W cross-section across the Arabian platform, showing the main time stratigraphic units and major unconformities (wavy lines). The cross-section extends from central Saudi Arabia to the middle of the Arabian Gulf; its location is shown in Figure 20.8 (Konert et al. 2001).

Source: Authors.

The Cambrian Hormuz salt layer is present in most of the Arabian Gulf as well as in the salt basins in inland Oman. Diapirs of Hormuz salt have risen to the surface in Iran and the southern Gulf; however, the tops of the salt diapirs in the northern Gulf lie extremely deep under the Dammam, Bahrain, Karan, Khursaniyah, and Hasbah domes (Stewart 2018). Hormuz salt in Saudi Arabia has not been penetrated by any deep wells and is too deep (>6000 m) for gas storage. Salt is also present in the Jurassic Gotnia Formation in Kuwait, but it does not extend significantly to Saudi Arabia (Al-Husseini 1997, Corley, Ye, and Kumar 2012).

The Arabian platform contains vast quantities of hydrocarbons in subsurface porous reservoirs that are mostly trapped within anticlinal structures. The two regional caprocks are anhydrite layers in the Khuff and Hith Formations. Unlike shale, pure anhydrite layers lack microporosity and are self-cemented. They also lack open fractures owing to the relative ductility of the anhydrite at depth. The effectiveness of these seals is demonstrated by the fact that although eastern Saudi Arabia contains the world's largest hydrocarbon accumulations, there are no natural oil or gas seeps; by contrast, oil seeps are present under the Arabian Gulf and along the Zagros fold belt because of leakage from Cretaceous and younger reservoirs. The effectiveness of these two regional seals enhances the potential for gas storage in aquifers and depleted or subeconomic gas reservoirs. However, most non-associated gas reservoirs in Saudi Arabia are in an early to intermediate production stage and will not be depleted in the near future. Furthermore, the reaction of hydrogen with anhydrite caprocks forms H_2S in reservoirs, which is undesirable for long-term hydrogen storage (Laban 2020).

The upper regional seal is the Hith Formation, which consists of anhydrite (also salt in the Gotnia Basin near Kuwait) and seals the Jurassic oil reservoirs in the majority of the structural closures in the Eastern Province at depths of 2,000–3,000 m. The lower regional seal is the Permo-Triassic Khuff Formation, which consists of a sequence of tight dolostones and anhydrites that also contain porous intervals in reservoirs A, B, and C (Konert et al. 2001). The depth of the Khuff aquifers increases eastward from 1–2 km near Riyadh to 3–4 km in the Eastern Province. The Khuff Formation traps vast quantities of gas in the Eastern Province, including Ghawar, Abqaiq, Qatif, and Dammam (see Figure 16 in Konert et al. 2001). In central Saudi Arabia, exploration wells targeting many anticlinal closures have shown that the Khuff Formation lacks hydrocarbons despite having adequate porosity in the A–C aquifers, which may be due to isolation from lateral migration pathways (Afifi 2010). These "dry" Khuff structures, particularly those located at shallower depths (<2000 m) in central Saudi Arabia, may provide options for short-term hydrogen storage.

Conclusion

Deep geological formations, including salt domes, saline aquifers, and depleted hydrocarbon reservoirs, can provide safe, reliable, and cost-effective large-scale storage for compressed hydrogen. Hydrogen storage in salt caverns is a mature technology that has been used for decades in various places. By contrast, hydrogen injection and storage in porous formations have yet to be demonstrated on a commercial scale. Various operational aspects of hydrogen injection, storage management, and withdrawal can benefit from the well-established storage technologies of natural gas in depleted gas reservoirs and saline aquifers. However, because of its distinct thermodynamic properties, hydrogen storage is less efficient than that of natural gas. Hydrogen requires a larger pore volume per unit mass under reservoir conditions because of its lower density than that of methane. Furthermore, its low viscosity may cause the inefficient management of surface and subsurface pressures during injection and withdrawal processes. Unlike natural gas, the fundamental bio-chemo-thermo-hydro-mechanical mechanisms resulting from hydrogen/brine/rock interactions in porous media under reservoir conditions have not been extensively studied. For instance, the mechanisms of hydrogen interaction with caprock and possible leakage from diffusion, wettability alteration/capillary entry pressure, and mechanical failure of the seal rock are not understood. The performance of various cushion gases such as methane, CO_2, and nitrogen and their interactions with hydrogen are yet to be determined. Therefore, the storage of hydrogen in a porous formation requires the rigorous characterization of the specific storage site with an in-depth understanding of all fundamental storage aspects, which is more challenging than storage in salt domes.

Saudi Arabia has the potential for subsurface hydrogen storage in solution caverns within shallow onshore salt diapirs along the Red Sea coast, including the sites of the Neom and Red Sea Development projects. The potential for subsurface hydrogen storage in the Central and Eastern Provinces is more challenging for several reasons: the Hormuz salt diapirs are evidently too deep, oil is present in Jurassic reservoirs, the non-associated gas reservoirs are far from being depleted, and storage in carbonate aquifers risks the possibility of forming H_2S by reaction with anhydrite. Nevertheless, such challenges could be overcome and further subsurface studies are needed. Therefore, the identification of suitable potential sites for hydrogen storage in the Arabian platform requires an in-depth knowledge of the subsurface from seismic data and well data as well as the evaluation of the hydro-thermo-chemo-mechanical processes associated with hydrogen storage in porous structures.

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21

GREEN HYDROGEN AND E-FUELS

A Saudi Arabian perspective

Shashank S. Nagaraja and S. Mani Sarathy

Introduction

The Paris Agreement provided the necessary impetus for countries worldwide to reduce carbon dioxide (CO_2) emissions and thus keep the rise in global temperatures within the specified limits. However, to meet the Paris Agreement targets, it is imperative to decarbonize the energy sector, as global energy-related CO_2 was 33.1 Gt in 2019 (IEA 2019), which is approximately 90% of all anthropogenic CO_2 emissions. In particular, since the transportation sector accounts for approximately one-quarter of energy-based CO_2 emissions, governments are recognizing the need to decarbonize sectors such as maritime and road transport, freight logistics, and aviation. Electrification is touted as a potential way to decarbonize the transport sector. However, even in the most ambitious decarbonization scenario in 2050 projected by BP (2020), electricity still accounts for 42% of the energy required by the transport sector. Hence, it is vital to switch to alternative low-carbon fuels produced sustainably from renewable feedstock.

Such fuels can be classified as biofuels and e-fuels. First, biofuels are produced from biomass or biological resources (Demirbas 2007). The most widely known and produced bio-alcohol is bio-ethanol (Melikoglu et al. 2016). A wide range of biomass such as lignocellulosic crops, residues, and food waste can be used to produce bio-alcohol. Bio-alcohols can also be used in solid oxide fuel cells (Raza et al. 2017), which are beginning to receive considerable attention owing to their high efficiency and low carbon emissions. However, the technology is not yet commercialized. Moreover, the pyrolysis or gasification of biomass can produce bio-hydrogen and bio-syngas (Maschio, Lucchesi, and Stoppato 1994; Wang et al. 1997) (a mixture of carbon monoxide and hydrogen). The transesterification of vegetable oils and animal fats produces biodiesel, an alternative to fossil-based

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diesel (Hoekman et al. 2012). Unfortunately, not even a tiny percentage of existing demand for transport fuels can be satisfied practically by biodiesel from waste cooking oil, oil crops, and animal fat due to limited feedstock availability. Therefore, research is examining how to produce biodiesel from microalgae and macroalgae at larger scales (Chisti 2007). Biogas and biomethane could be other biofuels produced mainly from waste and biomass residue (Ryckebosch, Drouillon, and Vervaeren 2011; Weiland 2010).

Second, decarbonizing the economy demands a large deployment of renewable energy sources (RES). As RES are intermittent, energy storage will play a vital role in converting surplus renewable electricity into a more convenient gas or liquid form. Power-to-gas and power-to-liquid technologies could provide an array of energy carriers while overcoming the intermittency of RES. Such liquid or gaseous fuels form another class of alternative fuels called e-fuels (Varone and Ferrari 2015). In power-to-gas technology, surplus power is used to electrolyze water to produce hydrogen. This form of hydrogen produced from renewable electricity via water electrolysis is called "e-hydrogen." E-hydrogen can react with carbon monoxide and CO_2 to produce methanol (Kauw, Benders, and Visser 2015). Methanol can then be used to produce high-demand hydrocarbons such as diesel, gasoline, and aviation fuels (Yarulina et al. 2018). Power-to-gas and power-to-liquid technologies can also provide a range of e-fuels for road, rail, air, and sea mobility. Although methanol cannot be used as a suitable engine fuel, these are not drop-in replacements and thus face compatibility issues with existing fueling infrastructure and logistics. Hence, the ideal drop-in fuels are expected to match the properties and composition of existing fossil fuels, which are typically nonoxygenated hydrocarbons.

Saudi Arabia has recently endorsed the circular carbon economy concept (Arab News 2020), which focuses on managing carbon, while sustaining the benefits of an oil and gas economy. Hence, carbon-neutral fuels such as green hydrogen, biofuels, and e-fuels are seen as a solution. Although Saudi Arabia has an area of about 2.1 million km^2, only 1.6% of the land area is arable (World Bank 2018), and revenue from forest products was negligible in 2018 (CIA 2022). Agriculture in Saudi Arabia focuses on the self-sufficiency of crops such as wheat, dates, vegetables, and fruit (Food and Agriculture Organization 2008). Owing to the arid climate, acute shortage of water, relatively cloudless skies, considerable temperature extremes, and wide seasonal variation, fuels produced from biomass are not commercially viable in Saudi Arabia. Hence, we focus on e-fuels and their role in decarbonizing the Saudi Arabian economy.

An important issue to raise is the efficiency of various fuel/powertrain solutions. Figure 21.1 compares the aspects of several options, including energy production, transmission, and end use. When renewable energy is available, direct deployment in battery electric vehicles is its most efficient use. Nonetheless, such technologies still face efficiency losses during electricity transmission in the grid, while storing energy can result in an additional 10% efficiency loss due to the intermittency of renewables. The hydrogen production efficiency from renewable energy

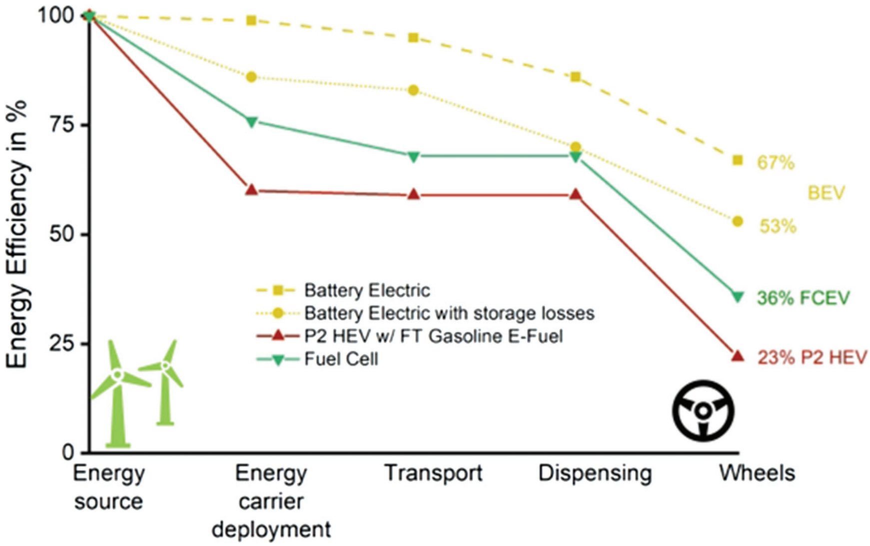

FIGURE 21.1 Energy efficiency of various powertrain solutions.

Source: Adapted from Rothbart (2020).

is typically 65%–80%, resulting in an immediate energy loss. Moreover, although the transmission of hydrogen for fuel cell electric vehicles is highly efficient, end use in such vehicles results in additional efficiency losses (more than in an electric powertrain). The conversion of hydrogen into an e-fuel results in further efficiency losses during production. Using an internal combustion engine in the vehicle also diminishes efficiency.[1]

Despite these efficiency losses, e-fuels are the only viable way to decarbonize heavy-duty transport and marine shipping until other options become available. This pathway is explored in this chapter.

Role of green hydrogen and e-fuels in the Saudi Arabian economy

Under the aegis of Saudi Vision 2030, the National Renewable Energy Program has been launched to increase the proportion of renewable energy in the energy mix.

The annual average global horizontal irradiation used to produce photovoltaic power is around 2,000 kWh/m^2 (Figure 21.2; KAPSARC 2020). Further, annual average wind speeds at heights of 40 m, 60 m, 80 m, and 100 m are 5.89 m/s, 6.24 m/s, 6.51 m/s, and 6.73 m/s, respectively (General Authority for Statistics 2018). The first stage of the National Renewable Energy Program has exploited the region's renewable energy potential; for example, the Sakaka project is commissioned to produce 300 MW from solar energy and the Dumat Al-Jandal project, which has a capacity of 400 MW from wind energy, is connected to the grid.

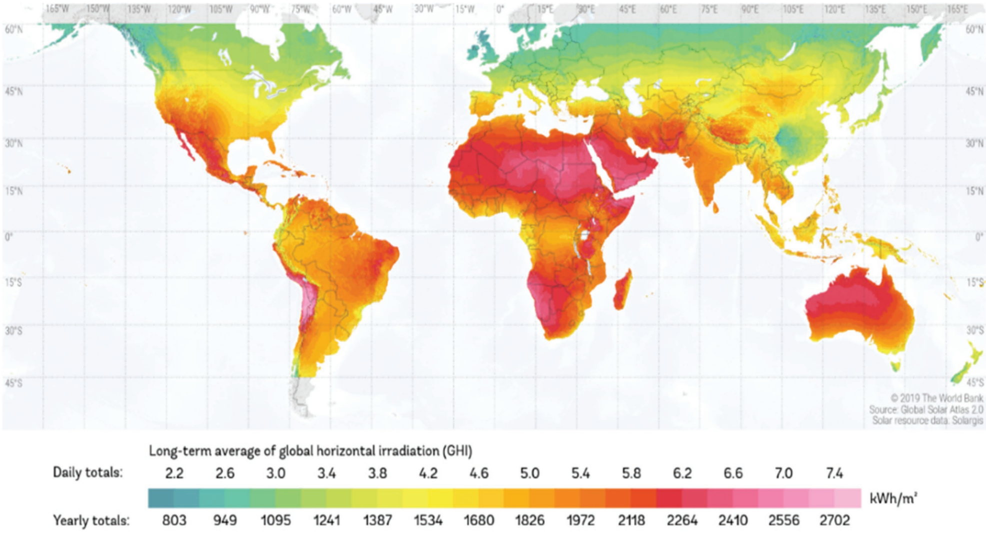

FIGURE 21.2 Global horizontal irradiation.

Source: ESMAP (2019).

The second phase of the project is expected to generate 1.5 GW of solar energy from Qurrayat, Jeddah, Rabigh, Alfaisalia, Rafha, and Madinah.

However, as noted above, energy generated from solar and wind is intermittent, while the storage and transportation of the renewable energy generated at isolated locations could hamper full-scale implementation. In addition, no large energy storage projects in Saudi Arabia exist. Hence, e-hydrogen is the missing link in this energy transition. Indeed, e-hydrogen[2] is being used not only to decarbonize several sectors but also to provide a plethora of chemicals and drop-in fuels in combination with other molecules. Hence, e-fuels produced from e-hydrogen will play a vital role as hydrogen vectors as the world moves toward cleaner fuels. Furthermore, e-hydrogen can be used to store energy, especially long-duration seasonal storage, and is more competitively priced than other technologies (e.g., batteries and geothermal).

The strategic consulting arm of PwC, Strategy&, estimates that global demand for green hydrogen could reach 530 million tons by 2050, replacing around 37% of pre-pandemic global oil production (Strategy& 2020). Moreover, the green hydrogen export market could be worth $300 billion annually by that year. This presents a tremendous opportunity for Saudi Arabia to become a leader in exporting e-hydrogen. Although the technologies needed to produce green hydrogen are common worldwide, the country has several advantages such as the availability of renewable energy with high yields, enormous areas of flat, barren land, easy access to desalinated seawater, and relatively low domestic consumption, which all provide scope for Saudi Arabia to become a market leader in this domain. Figure 21.3 illustrates the green hydrogen production potential of countries globally.

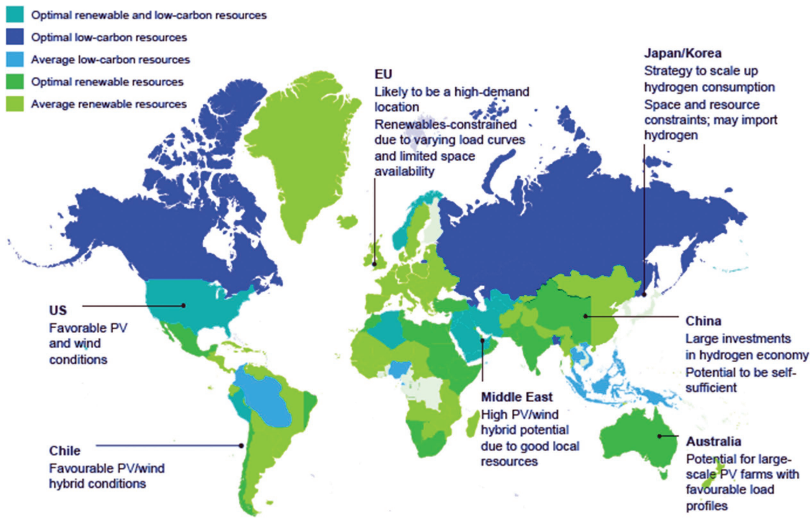

FIGURE 21.3 Green hydrogen production potential globally.

Source: Reproduced with permission from the Hydrogen Council (2020).

Although some countries such as China, the United States, and India plan to invest in green hydrogen production technologies, their export prospects are constrained by their huge domestic demand. By contrast, countries such as Canada, Chile, Australia, and member countries of the Gulf Cooperation Council have the potential to be net exporters of green hydrogen (Strategy& 2020; Figure 21.4).

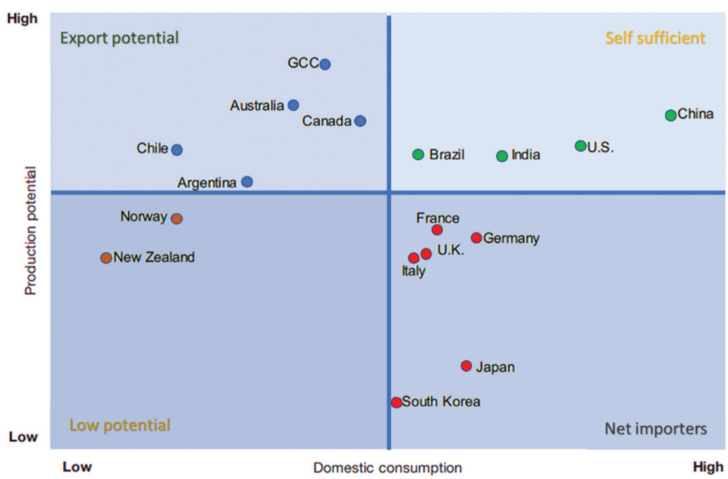

FIGURE 21.4 Green hydrogen export potential.

Source: Adapted from Strategy& (2020).

Saudi Arabia has taken the first step in this challenging task. A 650-ton/day e-hydrogen plant is being built at Neom, a new economic region in northwestern Saudi Arabia (Greentech Media 2020). This e-hydrogen can be converted into e-fuels either for domestic use or for export. Further, these e-fuels can be treated not only as drop-in fuels but also as energy vectors, thereby facilitating the transfer of abundant renewable energy from Saudi Arabia to other parts of the globe.

However, to produce e-fuels, e-hydrogen production is only the first step. CO_2, an important piece of the e-fuels puzzle, is relatively inert, making the conversion into e-fuels challenging (Ramirez, Mani Sarathy, and Gascon 2020). Additionally, the process efficiency and cost-effectiveness of the process pose a problem. The loss of process efficiency can be overcome by selecting ideal locations for generating electricity and sourcing CO_2 (Rothbart 2020). Middle-Eastern countries have the best locations for generating renewable electricity. Saudi Arabia's annual cement production capacity of 72.4 million tons is the highest in the Middle East. Cement industries are a major source of CO_2, with about 25 million tons of CO_2 being emitted from cement industries alone in 2019 (Andrew 2019). Further, the typical cost of CO_2 captured from cement plants is \$40–80/ton. However, for carbon-neutral e-fuels, the CO_2 must be sourced from air using direct air capture technology, which is expensive (\$300–500/ton). Significant advances in direct air capture are thus needed to drive the cost of capture.

The final cost of the e-fuel also depends on carbon pricing. The estimated price of EU carbon permits was €78.34/ton in March 2022. A scheme similar to the EU Emissions Trading System would enable the cement industry to implement mitigation measures and supply CO_2 to produce e-fuels. A carbon price of \$27/ton of CO_2 emitted is considered to be a viable compromise, which would generate \$4.9 billion for the government (Matar and Elshurafa 2017); this could be used to retrofit existing refineries near cement plants to produce e-fuels. Furthermore, improving the selectivity of catalysts would raise cost-effectiveness. In the next section, the technology required for the production of e-hydrogen and e-fuels is discussed.

To produce e-hydrogen, energy from RES is used in either an alkaline or a proton exchange membrane (PEM) electrolyzer to produce hydrogen and oxygen (Figure 21.5). State-of-the-art alkaline electrolyzers separate hydrogen using a saline solution, whereas PEM electrolyzers continue to use a solid membrane. Furthermore, alkaline electrolyzers have lower capital costs and higher efficiency than PEM systems. However, their dynamic operation is limited, and they have low current density and low operating pressures (<30 bar). The PEM method is preferred when used with electricity from RES due to its high current density (>1–2 A/cm^2), quick response, dynamic operation (0%–160% of nominal load), low temperatures (20–80°C), and capability to produce ultrapure hydrogen at elevated pressures (30–80 bar) (Khan et al. 2021). However, as the e-hydrogen produced has a high gravimetric density but extremely low volumetric density (Figure 21.6), it is not

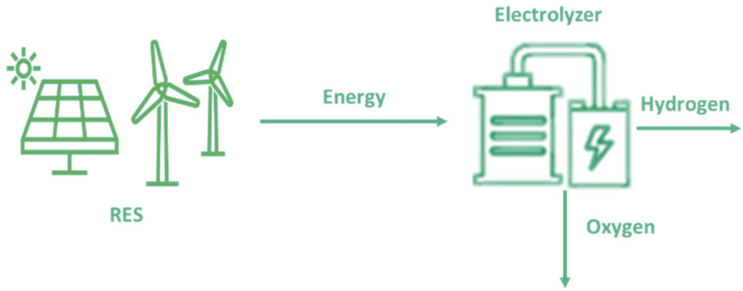

FIGURE 21.5 Schematic diagram of e-hydrogen production.

Source: Authors.

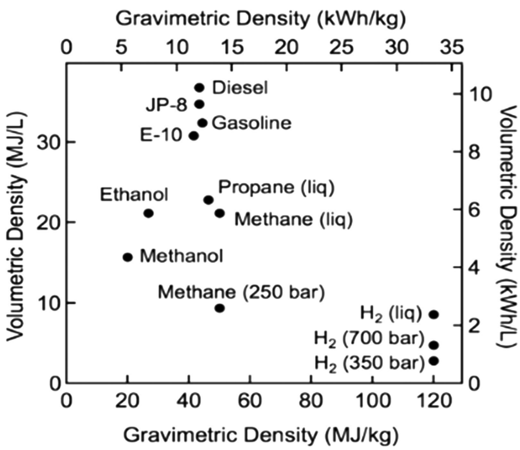

FIGURE 21.6 Gravimetric and volumetric density of different fuels.

Source: Department of Energy (2020).

economically viable to transport it over long distances. This makes e-hydrogen unsuitable for deep-sea marine transport and aviation.

To cope with these long-distance export and mobility issues, producers can convert e-hydrogen into ammonia, methanol, formic acid, and other liquid organic hydrogen carriers. Additionally, e-hydrogen can be converted into drop-in e-fuels for use in combustion engines without modifications. All these carriers enable the export of the surplus renewable energy from Saudi Arabia and could contribute to the decarbonization of different sectors worldwide.

Green methanol

Green methanol can be obtained from the reaction of e-hydrogen with captured CO_2, as shown in equation (1). A large plant for producing green methanol is run by Carbon Recycling International (CRI) in Iceland (Kauw, Benders, and Visser 2015; Tijm, Waller, and Brown 2001), and the technology has been demonstrated at the George Olah plant in the country. This is the first power-to-methanol plant in the world operating at 6 MWel, capturing 6,000 tons of CO_2, and producing 4,000 tons of CO_2 methanol per year. Its integration with the Svartsengi power generation plant (75 MWel and 150 MWhth) provides the necessary power, CO_2, and steam. Owing to the advantageous location of the Svartsengi geothermal plant, the quality of the CO_2 emitted and power for the operation make this a special operation. This helps decrease its CO_2 emissions, thereby using green power to create a green fuel. Specifically, e-hydrogen and CO_2 are compressed to 50 bar and heated to around 498 K. The unreacted mixture and products then flow through a distillation system, and the methanol is later condensed in a condenser:

$$CO_2 + 3H_2 \xrightarrow{\text{yields}} CH_3OH + H_2O \Delta H = -49 \text{kJ/mol} \quad (1)$$

The green methanol produced can be used directly for energy export. However, in the current scenario, this green methanol plant is only viable if e-hydrogen prices are below \$1.50/kg with no carbon pricing (Cordero-Lanzac et al. 2022). This price is achievable by 2030. The current cost of producing e-hydrogen in Saudi Arabia is \$2.41/kg (Hasan and Shabaneh 2022), and this will continue to fall with advancements in catalysts, electrolyzers, and renewable energy production.

Methanol, which had a demand of 83.8 million metric tons in 2020, is used mainly as a feedstock for different chemicals and has a well-established transport infrastructure (Prakash, Olah, and Goeppert 2011). Moreover, methanol could be further processed to produce drop-in e-fuels to be used domestically and exported internationally. As drop-in e-fuels can be directly used in present combustors, they are more attractive. Table 21.1 provides the hydrocarbon compositions of different drop-in e-fuels (Ramirez, Mani Sarathy, and Gascon 2020).

TABLE 21.1 Hydrocarbon composition for different drop-in e-fuels

E-fuel	*Hydrocarbon family*	*Composition range (vol%)*
Spark ignition engine	C_5–C_9 linear alkanes	10–20
	C_5–C_9 branched alkanes	40–50
	C_5–C_6 cycloalkanes	10–20
	C_7–C_9 aromatics	20–25
Compression ignition engine	C_9–C_{16} linear alkanes	35–50
	C_9–C_{20} branched alkanes	10–20
	Alkyl aromatics	20–30
	Alkyl cycloalkanes	20–25
Aviation engine	C_{10}–C_{12} linear alkanes	10–30
	C_{10}–C_{14} branched alkanes	20–40
	Alkyl aromatics	20–25
	Alkyl cycloalkanes	20–40

Methanol-to-Gasoline (MtG) process

To convert methanol into gasoline, the most suitable catalysts are medium-pore zeolites with considerable acidity. ZSM-5 is considered to be the most stable and selective catalyst. The process involves the conversion of methanol to light olefins using the dimethyl ether pathway. The smaller olefins formed undergo further transformation into higher olefins, C_3–C_6 alkanes, and C_6–C_{10} aromatics. Owing to the shape selectivity of ZSM-5, heavier hydrocarbons are not practically produced in the MtG process; hence, these could be used in spark ignition engines, as shown in (Prakash, Olah, and Goeppert 2011).

A plant based on Mobil's MtG process was built in New Zealand in 1979. This plant transforms natural gas from the Maui and Kapuni fields into methanol, and approximately 700,000 tons/day of gasoline is produced using Mobil's fixed-bed MtG process. The MtG gasoline produced is compatible with conventional gasoline. Further, the reaction is exothermic and has a heat reaction of about 1.74 MJ kg methanol (IEA 2019; Keil 1999). However, although nonzeolite catalysts have been employed, they cannot produce gasoline-range paraffins due to the associated side reactions (Galadima and Muraza 2015).

Industrially, catalysts such as H-ZSM-5 and H-SAPO-34 are used (Olsbye et al. 2012). The composition of the products depends on the zeolite topology. In the 1D 10 ring structure, intermediates are mainly alkenes producing $>C_3$ products, with the negligible production of aromatics. However, as the pore or cavity size increases, arene production takes over gradually, as intermediates lead to higher C_2/C_3 product ratios and an aromatic rich product mixture. The silicon-to-aluminum ratio in the zeolite affects the primary products of the MtG process (Benito et al. 1996). As this ratio increases, total acidity falls (i.e., the acidic site density decreases), and a higher proportion of heavier alkenes is thus produced. Additionally, larger crystal size zeolites are more shape-selective for catalysis reactions (Csicsery 1984). Furthermore, the surface modification of H-ZSM-5 with copper oxide increases the selectivity toward gasoline-range hydrocarbons but decreases the product yield (Zaidi and Pant 2005). Modifying the reaction conditions also changes the product composition in the MtG process, while increasing the pressure of the system leads to the higher formation of hydrocarbons with five carbon atoms or more. By contrast, olefin production is increased by the presence of water in the

TABLE 21.2 Product composition of ExxonMobil's MtG process

Product	*% composition*
C_1–C_2 light gases	1.3
LPG (C_3–C_4)	17.8
Gasoline (C_5–C_{12})	80.9
Diesel (C_{12}–C_{18})	0
Heavy oil (C_{19}+)	0
Oxygenates	0

feed. This also reduces the selectivity toward aromatics and paraffin production (Kianfar, Hajimirzaee, and Mehr 2020). Table 21.2 shows the typical yield of the MtG process (Brownstein 2015). Clearly, the MtG process is extremely attractive for producing gasoline-range drop-in e-fuels. However, when diesel range fuels and heavy oils are needed, Fischer–Tropsch (FT) synthesis is appealing.

FT process

FT technology is used to convert synthesis gas containing carbon monoxide and hydrogen into hydrocarbon products. The major benefits of FT hydrocarbons over crude oil as a fuel production feedstock are the absence of sulfur, nitrogen, and heavy metal contaminants as well as the low aromatic content. The jet fuel produced from the FT process has high smoke points and good combustion properties, and diesel fuel with its high cetane number can be used to upgrade lower-quality blend stocks produced from crude oil (Steynberg 2004). This process is unique, as two gases enter the reactor and a broad range of hydrocarbons exit. Performance depends on the feed, pressure, catalyst formulation, and operating temperature. The FT process can then be largely classified into three basic steps: (i) syngas preparation, (ii) FT synthesis, and (iii) product upgrading.

Historically, the FT process was carried out using fossil fuel-derived syngas on a fixed bed or a fluidized bed reactor with either a cobalt or an iron-based catalyst. FT reacted coal with steam to produce synthesis gas (a mixture of carbon monoxide and hydrogen) in a hydrocracking process and then transformed the gases into petroleum-like synthetic liquid at pressures of 1–10 atm and temperatures of 453–473 K. The process was first designed and developed by them with a cobalt catalyst (Mahmoudi et al. 2017). Chemically, FT synthesis is a surface polymerization reaction in which the reagents react on the surface of the catalyst in situ. Recently, carbon monoxide produced from a reverse water gas shift reaction from CO_2 has been reacted with e-hydrogen to produce FT diesel. The CO_2-based direct FT process has also been investigated (Choi et al. 2017). Indeed, Sasol continues to operate a synfuels plant in South Africa, illustrating the maturity of the FT technology. If the aim of the country is to produce an automotive fuel or a liquid energy carrier, the MtG process is far more attractive than FT synthesis (Brownstein 2015).

To compete with traditional sources of energy, economic and social incentives are necessary for RES. Developments in electrolysis technologies, especially PEM technology, have increased efficiencies and operational lifetimes. However, research on new and cost-effective materials that should reduce the capital costs per kilowatt to as little as $200 by 2050 is needed (Strategy& 2020). Additionally, better reactors and catalysts are required for methanol synthesis and the MtG process. Furthermore, research is needed on how to eliminate side reactions in the FT process. Saudi Arabia, as a pioneer in the petrochemicals sector, could use its expertise to facilitate research on reactors, reaction engineering, catalyst selection, and design.

Pilot plants and case studies

George Olah Methanol Plant

CO_2 can be converted into methanol by hydrogenation over heterogeneous catalysts using e-hydrogen. Methanol can be produced using catalysts based on copper–zinc oxide–alumina at 220–250°C and a bar pressure of 10–30 (Olah 2013). CRI, which was founded in 2006 in Iceland, produces renewable methanol (4 kt/year) based on this technology (Figure 21.7). The methanol produced by CRI is called Vulcanol and has been sold commercially since 2012. The conventional production of methanol emits up to 4 tons of CO_2 for each ton of methanol produced. On the contrary, the CRI plant consumes 1.4 tons of CO_2 for each ton of Vulcanol produced. Furthermore, Vulcanol is an efficient energy carrier that can easily store and transport off-peak renewable energy (mainly geothermal in Iceland), thus stabilizing the power grid and supporting the expansion of RES. A similar plant based on hydrogen produced from solar and wind energy could be implemented in Saudi Arabia.

Haru Oni project (consortium of AME, Enel Green Power Chile, ENAP, Siemens Energy, and Porsche)

The Haru Oni pilot project in the Magallanes province in southern Chile takes advantage of the conducive environmental conditions (i.e., excellent climatic

FIGURE 21.7 George Olah Methanol Plant.

Source: CRI.

conditions for wind power) to produce a fuel that is claimed to be climate-neutral (Bioenergy International 2020). Andes Mining & Energy (AME), the owner of the project, is supported by Empresa Nacional del Petroleo (ENAP) (providing operating staff and logistics) and Siemens Energy (systems integrator to serve the entire value chain). Siemens Gamesa wind turbines will generate the power to be utilized in a PEM electrolyzer to produce e-hydrogen. In the second phase of the project, direct air capture technology will be used to obtain CO_2 to produce e-methanol. The project will finally be supported by ExxonMobil to convert methanol into gasoline using proprietary MtG technology. Porsche will be the primary consumer of the green gasoline. In the pilot phase, around 130,000 liters of e-fuels are expected to be produced in 2022. In the next two phases, capacity will increase to about 55 million liters of e-fuels per annum by 2024 and to around 550 million liters by 2026 (Recharge News 2020).

Yara Pilbara (Yara and Engie)

Yara and Engie have announced the Yara Pilbara ammonia plant to supply green ammonia to exploit Australia's renewable energy potential. The plant is scheduled to commence production in 2023 and will produce up to 625 tons of renewable hydrogen and 3,700 tons of renewable ammonia per year. This initial phase is crucial to enable the facility to become a green ammonia and hydrogen hub, building on the existing export infrastructure (Yara International 2020).

Saudi Arabia can learn from these pilot plants and case studies to establish itself as an e-hydrogen and e-fuels hub by setting ambitious and realistic capacity targets based on global market trends. Further, a clearly defined governance and institutional framework with pragmatic policies and regulations would aid the integration of green fuels into the existing energy system. With its renewable energy potential, necessary policies, and infrastructure, Saudi Arabia could then become a global leader in exporting e-hydrogen and e-fuels.

Conclusion

The world is moving toward a decarbonized mobility sector; however, the electrification of long-distance transportation is improbable. Given its geographical location, Saudi Arabia can exploit its sustainable energy sources to produce green hydrogen; however, the volumetric energy density of hydrogen is unsuitable for its direct implementation in sectors such as aviation and maritime. Furthermore, a transportation infrastructure for hydrogen must be developed. The technologies and processes available to convert hydrogen into e-fuels, as explored in this chapter, could provide an unparalleled opportunity for pioneers such as Saudi Arabia to dominate the world market in cleaner liquid fuels.

Notes

1 Consequently, e-fuels in combustion engines have the lowest roundtrip efficiency. Note that hydrogen combustion engines are not mature technologies because of low power densities, which is not an issue in liquid fuel-fired engines. The aforementioned analysis is only applicable to renewable energy that is readily available and where battery electric/fuel cell solutions are mature. Neither is the case for heavy duty transport or large marine vessels. The only viable powertrain technology in those cases, today and in the foreseeable future, is the internal combustion engine.

2 Green hydrogen is carbon-neutral hydrogen produced from either biomass or water electrolysis using electricity from RES, and e-hydrogen is the green hydrogen produced from water electrolysis using electricity from RES.

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22

THE POTENTIAL ROLE OF HYDROGEN IN DECARBONIZING HEAVY INDUSTRY IN SAUDI ARABIA

Bassam Dally

Introduction

The quest to decarbonize energy-intensive sectors, particularly industrial sectors, has gained unprecedented attention over recent years. According to the United Nations Framework Convention on Climate Change (UNFCCC), 194 countries have submitted nationally determined contributions covering 90% of global energy-related industrial carbon dioxide (CO_2) emissions, NDC Registry (2022). Additionally, an increasing number of shareholders apply environmental, social, and governance considerations to evaluate major global corporations' commitment to sustainability. Many such corporations are involved in heavy industry such as mining, mineral processing, and petrochemicals. This market pull has created additional incentives to accelerate the decarbonization process, resulting in bold and ambitious targets for many of these firms. For example, the top three mining companies globally, Glencore, BHP, and Rio Tinto, account for two-thirds of mining revenues globally. They have pledged to achieve net-zero operational greenhouse gas emissions by 2050 (Scopes 1 and Scope 2 from operated assets). In Saudi Arabia, the government has announced carbon neutrality by 2060, while Vision 2030 stipulates that 50% of power generation must be from natural gas and renewables by 2030. Heavy industry in Saudi Arabia has also announced aspirational targets to decarbonize operations. The two largest companies, Saudi Aramco and Saudi Basic Industries Corporation (SABIC) have pledged carbon neutrality in Scopes 1 and 2 by 2050, while the largest mining company, Ma'aden, has adopted a sustainability strategy that includes reducing carbon.

According to UNFCCC (2020), the industrial sector in Saudi Arabia contributes 53.5% of annual CO_2 emissions. An estimated 12.5% of this CO_2 is emitted directly from industrial processes (e.g., cement manufacturing) and the rest is generated by

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TABLE 22.1 CO_2 emissions in Saudi Arabia by sector, 2016

Sector	*CO_2 emitted (Mt)*	*Percentage*
Electricity generation	161.0767	26.72
Road transport	133.0124	22.07
Desalination	103.6339	17.19
Petroleum refining	39.729	6.59
Petrochemical (fuel combustion)	29.8452	4.95
Cement production	28.6092	4.75
Petrochemical production	24.6911	4.10
Fertilizer (fuel combustion)	17.1357	2.84
Cement (fuel combustion)	12.9343	2.15
Iron and steel production	9.9117	1.64
Ammonia production	9.2195	1.53
Well testing (fugitive emissions)	5.4839	0.91
Other	27.533	4.57
Total	602.816	100.00

Source: UNFCCC (2022).

fossil fuel combustion. Table 22.1 lists CO_2 emissions by sector in Saudi Arabia. Although the only publicly available official data are from 2016, the percentage contributions from each sector remain closely related to the percentages found today. Further analysis of the 2016 data by Rahman et al. (2022) highlighted the three major emission sources: power generation (including industrial processes), road transport, and desalination. However, Table 22.1 also highlights the high emissions from heavy industry, particularly the petrochemical, cement, iron and steel, and fertilizer sectors.

Figure 22.1 illustrates the global CO_2 emitted by sector in 2016 and change projected for 2050, assuming the 1.5°C warming scenario. The data for the industrial sector are split into process-related emissions (e.g., CO_2 from limestone calcination) and energy-related emissions. The energy is mostly in the form of thermal energy that is needed to drive ores' reduction and manufacturing processes. The figure shows that CO_2 emissions from the power sector are expected to reduce from 34% to 17% by 2050. However, the contribution of the industrial sector is predicted to increase from 34% of all the CO_2 emitted to 59% by 2050, becoming the most prominent source.

This figure also shows the contributions of the four main sectors: steel, minerals (e.g., iron, cement, and copper), alumina, and other chemicals. As shown in Table 22.1, the main contributors to industrial CO_2 in Saudi Arabia are the same, albeit at different proportions. Petrochemicals account for 14.1% of CO_2 emissions, cement 6.9%, fertilizers and ammonia 4.37%, and steel 1.64%. In Saudi Arabia, all iron pellets are imported because low-quality indigenous iron ores require beneficiation before they can be used.

Multiple strategies are needed to reduce carbon emissions in each of these major emitting sectors. The power sector has received most of the attention and investment

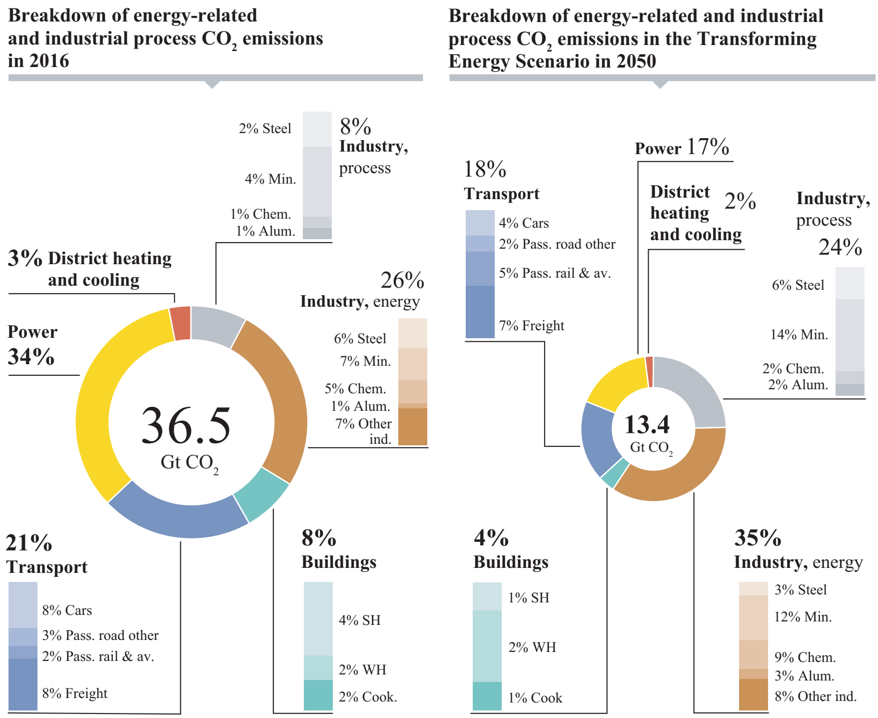

FIGURE 22.1 CO_2 emissions in 2016 and projected to 2050 by sector.

Source: IRENA (2020).

in solar, wind, and hydroelectric renewable sources, which are playing a critical role in its decarbonization. The transport sector is also being decarbonized at an increased rate, with electrification and hydrogen fuel cells as the main energy sources to replace internal combustion engines. In industry, both power and thermal energy are required to drive different manufacturing processes. It is estimated that 74% of the energy needed by industry is in the form of thermal energy (equating to approximately 85 exajoule [EJ] annually), and that 48% of this energy is needed at temperatures above 400°C (Philibert 2017). In other words, more than 40 EJ of heat is required annually, which is currently provided almost exclusively by the combustion of fossil fuels. Identifying alternative low-carbon sources for this heat poses a major challenge for both industry and technology providers. Part of the challenge is related to the difficulty of retrofitting and adapting new energy sources at such scale. Potential low-carbon alternative heat generation sources include electrification from renewable sources, solar thermal energy, and low-carbon fuels (e.g., hydrogen, ammonia, and biofuels).

Table 22.2 summarizes the role of electrification, hydrogen, ammonia, solar thermal, and biofuels in decarbonizing different sectors. The technology readiness levels (TRLs) for each measure are added in parentheses. Hydrogen has major

TABLE 22.2 Potential for reducing carbon in selected heavy industries. Numbers in parentheses indicate the TRL

	Direct electrification	*Solar thermal*	*Hydrogen*	*Ammonia*	*Biofuels*
Iron and steel	Electric furnaces (9) Direct reduction iron (9) Plasma reduction (3)	Heat source (5)	Reductant (9) Heat source (7)	Reductant (4) Heat source (4)	Heat source (4)
Cement	Electric kilns (3)	Direct calcination (3)	Heat source (4) Steam calcination (3)	Heat source (4)	Heat source (9)
Alumina	Electric heating (4)	Indirect Bauxite calcination (6)	Heat source (6) Steam calcination (5)	Heat source (4)	Heat source (4)
Petrochemicals	Electric furnaces (3)	Heat source (4)	Heat source (6) Chemical (9)	Heat source (4)	Heat source (4)

Source: Author.

advantages in the heavy industry sector, not only as a heat source but also as a reductant agent (especially in iron production). Electrification can play an important role, albeit partially, and with limited capacity due to the 24/7 operating mode of these industries. The table does not imply techno-economic viability but rather the potential for adaptation in the future. The TRL indicates the options that have been commercialized and those still under development. In addition, the rate at which some of these options can be adapted to industry differs markedly. For example, biofuels can be adopted relatively quickly if and when they become available at a competitive price and the required scale, while solar thermal applications require major integration and development to be proven viable.

This chapter focuses on the role hydrogen can play in decarbonizing heavy industry in Saudi Arabia. It particularly focuses on the cement, iron and steel, phosphate, and aluminum sectors because of their relevance to Saudi Arabia and the planned expansion of these industries in the future. Hydrogen utilization in the petrochemical industry is well established and is not discussed in this chapter.

Role of hydrogen in Saudi Arabia

Opportunities and barriers

Heavy industry is capital-intensive, trade-exposed, and risk-averse. The adaptation of new fuels and technology at scale can take decades and is fraught with risk. Beyond the inevitable technical risks associated with any new technology, there are also risks associated with the supply chain of alternative fuels, changing government policies, market demand, and international regulations. Hence, the low-risk adaptation of hydrogen is an essential first step to provide sufficient certainty to invest in the long term. Many industrial processes have been optimized over decades to maximize profits and throughput, with less attention paid to fuel type and emission footprint. Hence, decarbonization will also require rethinking well-established processes and reoptimizing them by accounting for emission reductions and low carbon intensity without compromising quality, safety, and productivity. As new innovative low-carbon technologies are developed, the opportunity to rethink existing processes, incorporate additional efficiency gains, and make adaptation cost-neutral arise. Such an approach is desirable for both industry and end-users. It can be achieved through accelerated development and scaling, supported by computational tools, to avoid costly and protracted iterative trial-and-error approaches. Research funding and collaboration with technology companies and end-users are the key factors to achieving this objective.

As shown in Table 22.2 and mentioned earlier, hydrogen, as a carbon-free fuel, is needed both as a reductant to replace carbon-based chemicals and as an energy source, especially for processes that require high temperatures (>400°C). These temperatures are common in the reduction of iron, copper, and other minerals as well as the calcination of limestone, cement, and alumina. Hydrogen is also necessary to produce steel, glass, fertilizers, and other chemicals. It offers considerable advantages over fossil fuels owing to its wide flammability limits, flame stability, and adaptability. Hydrogen can also be blended with existing fossil-fueled combustion systems at varying percentages with relatively minor modification to the process. This process allows an intermittent supply in the transitional stage toward carbon-free processes. Such flexibility will help gradually introduce hydrogen to different heavy industry sectors. This will increase the familiarity of industry with hydrogen and its use as well as support the staged scaling up of the supply chain and storage. In addition, it will davoid the need for risky investment in new and costly infrastructures in the near term. Nonetheless, hydrogen adaptation is not without its reasonably addressable challenges. These include the cost of storage, low volumetric density, sealing and safety considerations, metal embrittlement, thermal NOx emissions, and low flame radiation. Mature solutions for these challenges are available and mostly affordable, although they are process- and industry-specific and require further development to be adopted.

Heavy industry in Saudi Arabia

Crude steel production in Saudi Arabia was 8.2 million metric tonnes in 2019, an increase of 3.4 million metric tonnes from 2017 (World Steel Association 2020). This level of production is relatively small in global terms, accounting for only approximately 0.4% of steel production worldwide in 2019. Global crude steel production was 1.95 billion metric tonnes in 2021 and it is responsible for between 7% and 9% of human-generated CO_2, according to the World Steel Association (2019, 2022). SABIC Hadeed is the largest producer of steel in Saudi Arabia, accounting for 5.8 million metric tonnes of the country's production. The majority of this steel is used within the Kingdom and the rest is exported, mainly to the Middle East and North Africa (MENA) region. While Saudi Arabia has large reserves of low-grade iron ore nationally, it is not used in steelmaking; instead, pellets are imported from Brazil (via Oman), Sweden, and Africa.

Saudi Arabia produces approximately 70 million tonnes of cement annually. It is the largest producer in the MENA region and the eighth largest producer globally, accounting for approximately 1.25% of global production. The main contributors to CO_2 emissions from cement manufacturing are the calcination of limestone and clinker (50%); combustion to drive the high-temperature process (40%); and power for grinding, preparation, and transport (10%). On average, a tonne of cement results in the emission of 600–900 kilogram (kg) of CO_2 depending on the type of clinker, combustion process, and waste heat recovery. In Saudi Arabia, the clinker factor, which measures the fraction of limestone in clinker, is 90% which makes the carbon intensity of Saudi-produced cement very high. An estimated 8% of the CO_2 emissions in Saudi Arabia come from cement manufacturing.

In 2020, Saudi Arabia produced 999,000 metric tonnes of aluminum and consumed 638,000 metric tonnes (World Bureau of Metal Statistics 2021). Ma'aden operates an aluminum plant in Ras Al Khair in partnership with Alcoa. The company claims to have built the world's most efficient and integrated aluminum complex. The project includes a bauxite mine, refinery, smelter, casthouse, can recycling unit, and the world's most advanced rolling mills. The alumina produced is purported to be of very high standard and is sold to domestic and global markets. Natural gas is the fuel used in gas-fired power generation, calcination, and smelting. Global average CO_2 emissions for both virgin and recycled aluminum are 11.5 tonnes of CO_2 per tonne of aluminum (Clemence 2019; Ping et al. 2019).

Saudi Arabia has large reserves of phosphate, which are used to produce fertilizers. The Ma'aden Phosphate Company operates in two primary locations in the Kingdom: Al Jalamid in the Northern Province, where its phosphate mine and beneficiation plant are located, and Ras Al Khair Industrial City in the Eastern Province, where its integrated fertilizer production complex is located. Ma'aden's phosphate mine produces close to 11.6 million tonnes of ore per year (sixth largest in the world, accounting for approximately 6% of global production), while the beneficiation plant produces up to 5 million tonnes of concentrated phosphate rock per year. Ma'aden's integrated fertilizer production complex includes each of the following plants: phosphoric acid, sulfuric acid, ammonia, diammonium phosphate, granulation, and desalination. The Ma'aden Phosphate Company can produce 3 million tonnes of diammonium phosphate annually, most of which is sold in the international market.

The Ma'aden Wa'ad Al Shamal Phosphate Company is located in the Wa'ad Al Shamal Minerals Industrial City in the Kingdom's Northern Province. The complex includes seven world-class plants and associated facilities, including plants for beneficiation, phosphoric acid, sulfuric acid, diammonium phosphate, and granulation. These plants make up one of the largest phosphate production complexes globally. The Ma'aden Wa'ad Al Shamal Phosphate Company can produce 3 million tonnes of fertilizer products such as diammonium phosphate, monoammonium phosphate, nitro phosphate, nitrogen, phosphate, and potassium fertilizers. With the commissioning of the Ma'aden Wa'ad Al Shamal Fertilizer Production Complex, Ma'aden became a leading player in the global phosphate market. CO_2 emissions from the fertilizer industry depend heavily on the product type and integrated nature of the plant (Wood and Cowie 2004).

Hydrogen as an alternative fuel/reductant in Saudi Arabia

When considering the challenges and opportunities of hydrogen adaptation to decarbonize heavy industry in Saudi Arabia, it is important to consider both economic and practical aspects. On the economic side, the cost of energy and fossil fuels in Saudi Arabia is far lower than alternative energy sources, including hydrogen. Hence, there needs to be a strong business case for hydrogen to be used in heavy industry in the Kingdom. Such a scenario is unlikely to occur in the next decade or so considering the projected hydrogen price and level of supply. Locally produced hydrogen is more likely to be traded in international markets with higher profits than that used to replace cheap indigenous fossil fuels in Saudi Arabia. Moreover, other measures can be used to decarbonize industry beyond the use of hydrogen, and such measures are likely to be used first by various heavy industries, as part of their commitment to reduce carbon emissions. This could occur in the form of efficiency gains, carbon capture, and other alternative fuels (e.g., waste and biomass).

Another important consideration in Saudi Arabia is related to the supply chain and possible location of hydrogen production facilities relative to where it will be used. For example, there are two potential sites for hydrogen production in Saudi Arabia: one in the Dahran region, where blue hydrogen is being produced, and one in the northwest, where green hydrogen will be produced. However, heavy industry is widespread nationally and transport is only possible by land or via a pipeline. The inevitable additional costs are thus expected to increase the cost of using hydrogen as a replacement for the existing and well-established fossil-based energy systems.

Another important factor is that many heavy industry infrastructures are relatively new and state of the art. For example, Ma'aden was only established in 1997 and many of its subsidiaries and mines are less than 15 years old. All iron reduction processes in Saudi Arabia use the direct reduction iron (DRI) process, which is the best low-carbon commercial technology available in the market. All cement kilns in Saudi Arabia use dry calcination, which is more energy efficient than older wet calcination processes. In other words, the industry has invested in infrastructure with the latest technology and, understandably, would be reluctant to change to new fuels and processes so soon. This novel feature of Saudi Arabian heavy industry has direct implications for the country's decarbonization strategy and hydrogen use.

Other general issues to consider include the need to demonstrate hydrogen utilization at an industrial scale, additional local safety procedures for using hydrogen on site, and the lack of familiarity with this fuel, requiring training and social licenses to operate. Some of these gaps can be addressed gradually through blending, where possible, which allows for a transitional approach and de-risking in the change process. For example, safety issues, familiarity, and the effect on chemical processes can be mitigated gradually as more hydrogen is produced and used.

In the next section, the utilization of hydrogen in the steel, cement, aluminum, and phosphate industries is addressed, highlighting the technology options and Saudi Arabia-specific issues related to adaptation.

Hydrogen utilization

Iron and steel industry

Manufacturing one tonne of crude steel emits 1.85 tonnes of CO_2 when current carbon-based technology is used. Globally, Bloomberg NEF (2021) argued that steel production could—with $278 billion extra investment by 2050—be made with almost no carbon emissions; however, this would require the additional use of hydrogen as an energy source and further recycling of steel. According to this report, green hydrogen could be the cheapest method of producing steel and could capture 31% of the market by 2050. It also suggests that, in theory, 45% of steel could be sourced from recycled material and the rest from "a combination of older, coal-fired plants fitted with carbon capture systems and innovative processes using electricity to refine iron ore into iron and steel" (Bloomberg NEF 2021).

Figure 22.2 shows the different routes of iron reduction and steel manufacturing, particularly the number of steps required, temperature needed, and amount of oxygen and carbon bonded with iron in each stage. The current two-stage approach requires a blast furnace to generate hot molten metal before it is fed into a basic oxygen furnace to convert it into steel. Similarly, when using the direct reduced iron (DRI) approach, the second step involves using an electric arc furnace to generate the steel. A blast furnace uses coke and additional heat from natural gas and is carbon-intensive. The DRI process uses natural gas, which is converted into syngas or hydrogen and thus avoids the high temperatures required in blast furnaces.

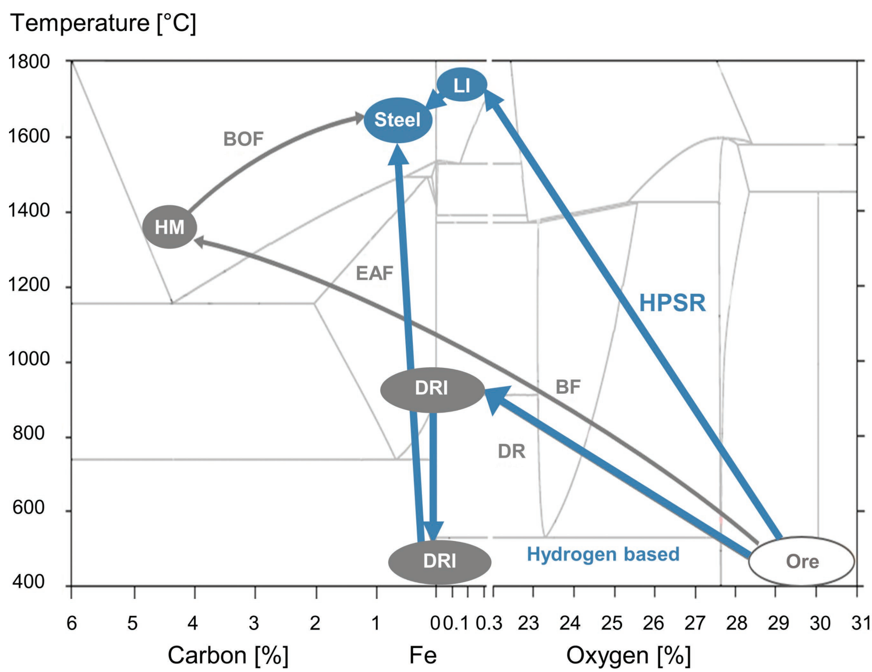

FIGURE 22.2 Steel production process through different pathways. BF: blast furnace, BOF: basic oxygen furnace, EAF: electric arc furnace, HM: hot metal, DRI: direct reduced iron, HPSR: hydrogen plasma smelting reduction, LI: liquid iron.

Source: Johannes Schenk and Michael Zarl, K1-MET GmbH, Leoben, Austria, personal communication (May 2021).

An alternative one-step smelting technology that uses hydrogen almost halves the energy requirement. It also reduces CO_2 emissions and allows the integration of renewable fuels and electricity. Two examples of such processes are hydrogen plasma smelting reduction and the metal oxide electrolysis of Boston metals. Table 22.3 describes the technology pathways for decarbonized steelmaking as well as their TRLs and potential benefits. The table shows that carbon capture technology is mature and readily available for deployment soon, albeit at a high cost. In addition, this approach requires additional infrastructure for transporting and storing CO_2 which is site-specific and not commercially available. On the other hand, hydrogen-based direct reduction is readily available and can be deployed over a relatively short period at a competitive cost. Other low-TRL technologies mostly associated with one-step reduction have great potential and further investment in developing them is warranted.

In Saudi Arabia, most steel reduction occurs using natural gas in the DRI process and an electric arc furnace. As mentioned above, direct reduction refers to solid-state processes that reduce iron oxides to metallic iron at temperatures below its melting point. In DRI, natural gas is reformed and used in either Midrex or Tenova HYL technology at various hydrogen-to-carbon ratios. In DRI, reductant gases such as hydrogen, syngas, and coal are used to convert hematite (from iron ore) into magnetite. Magnetite is then converted into ferrous oxide and finally into iron. The reduction occurs with solid iron ore and temperatures of 800°C–1,200°C, which is below the melting point of iron (1,538°C). The carbon intensity per tonne of hot-rolled coils of steel using the HYL process (using natural gas) is 984 kg of CO_2, whereas it is 1,557 kg of CO_2 using the traditional blast furnace/basic oxygen furnace. Although demonstration plants of hydrogen-DRI exist in Sweden (HYBRIT), Germany (Midrex), and China (in collaboration with HYL Tenova), no commercial plants operate purely on hydrogen. Instead, Midrex and others are planning to blend hydrogen with syngas from natural gas to increase its use in the transitional phase. According to Midrex (2022), up to 90% of natural gas can be replaced with hydrogen in the modified DRI process. The only barrier relates to the cost of hydrogen and lack of a hydrogen infrastructure. However, using hydrogen-DRI for reduction and hydrogen for heating in steel manufacturing would reduce carbon emissions from steel to extremely low levels.

A pure CO_2 stream is produced by the HYL process and this CO_2 can be stored in the slag produced in the same plant for up to 30% by mass depending on the level of calcium oxide in the slag. This carbonation process is semi-commercial and can offer a transitional option for storing CO_2. SABIC Hadeed's (2018) study found that without direct subsidies, carbon pricing, or a niche market for green steel, the switch to green hydrogen is too costly and therefore unviable, at least in the near future.

In summary, the barriers to the decarbonization of steelmaking are mostly related to the cost of hydrogen and clean power rather than the availability of technology. For Saudi Arabia, a transitional plan is needed to incentivize the adoption

TABLE 22.3 Carbon reduction options for steelmaking.

		Technology readiness	*Years until plateau of productivity*	*Development cost*[1]	*CAPEX requirements*[2]	*Operating costs*[3]	*Public acceptance*	*Possibility to transform brownfield plant*
CCUS	Carbon capture, use, and/or storage	2/3	5–10	1/2	1/3	2/3	1/12	11/12
	Carbon capture, use and/or storage with biomass	1/2	5–10	2/3	1/2	1/3	0	3/4
Alternative Reductant Agent	Hydrogen-based direct reduced iron: Shaft furnace	11/12	0–3	1/12	1/3	1/4	3/4	3/4
	Hydrogen-based direct reduced iron: Fluidized bed	2/3	5–15	1/3	1/3	1/4	3/4	3/4
	Suspension iron-making technology	1/4	17–22	3/4	1/4	1/4	3/4	1/4
	Plasma direct steel production	1/12	20–25	11/12	1/4	1/12	3/4	1/4
	Electrolytic processes	1/4	20–30	3/4	1/4	1/4	3/4	1/12

Source: Berger (2021)

1 Compared with the other presented carbon neutral technologies.
2 Compared with the CAPEX of a BF-BOF greenfield plant in 2040–2050.
3 Compared with a BF-BOF plant in 2040–2050 (including carbon tax).

LOW HIGH

of hydrogen as an iron reductant, supported by access to renewable energy for steel production. In the interim, as excess blue hydrogen becomes available and the price drops further, blending with natural gas will become a viable strategy. This is because it does not require major investment in infrastructure and will reduce CO_2 emissions from steelmaking.

Cement industry

The plants used for cement manufacturing in Saudi Arabia are relatively efficient. Most include a stage cyclone suspension preheater and calciner, while some have high-efficiency coolers, which require an average heat input of 3,200 MJ/tonne of clinker. Saudi Arabia's 24 cement plants operate on a variety of fuels, including heavy fuel oil, crude oil, and natural gas. Few cement plants use alternative fuels such as recycled shredded tires, petcoke, and other waste. There are four main avenues for reducing CO_2 emissions in the cement industry. The first relates to energy efficiency and using state-of-the-art cement kilns, particularly dry cement kilns instead of wet and semi-wet kilns. The second relates to using low-carbon intensity (natural gas) and alternative fuels (biomass and waste) as well as renewable electricity in the manufacturing process. The third relates to replacing the clinker in the cement with other minerals (e.g., clay, blast furnace, steel slag, red mud, and fly ash) to reduce the amount of CO_2 emitted from the process itself. For example, suitable clay can be sourced from various locations and its calcination does not emit CO_2. The study by EPFL in Switzerland found that a particular blend, termed LC3, which uses 40% clay in cement, has the same properties as ordinary Portland cement used in the industry today (LC3 2022). The fourth strategy involves the capture of CO_2 from exhaust emission for use or storage, either when oxy-fuel combustion is used for the calcination process or for the postcombustion capture of fuel-air combustion. Another approach to capture CO_2 at a reasonable cost involves using indirect heating for calcination (known as Calix technology and termed LEILAC). Here, heat from the combustion of fossil fuels or from electrical energy is used to externally heat the flash calciner, where finely ground limestone particles are heated. This causes CO_2 to be released and then captured. These technologies are relatively mature (TRL of 7–9). All such capture approaches are plausible interim measures once cost and scale have been resolved. Nonetheless, it is imperative to highlight the extent of the challenges of carbon capture and storage. For example, substantial infrastructure and investment are needed to capture, transport, and store 5,000 tonnes of CO_2 per day from an average cement plant.

Integrating hydrogen into cement manufacturing is low on the priority list for decarbonization strategies because of the high cost of hydrogen, industry size, and requirement for additional infrastructural investment. Unlike the steel industry, which requires specific chemicals to provide heat and act as reductants, cement production requires high-temperature heat at approximately 1,600°C, irrespective of the fuel type. Today, low-cost subsidized fuels are used for cement manufacturing in Saudi Arabia. Replacing them with carbon-free fuels such as hydrogen is unviable in the foreseeable future.

Hydrogen can play a role in decarbonizing cement manufacturing in niche opportunities. This includes the firming up of power networks when renewable sources such as solar and wind are unavailable. Under this approach, hydrogen is produced when an oversupply of renewable energy exists and is then stored for periods when neither wind nor solar energy is available. Hydrogen production, storage, and utilization technologies are at a mature stage (TRL of 7 or 8).

Another emerging option is steam calcination, which involves burning the hydrogen and oxygen produced via electrolysis (Provisional Patent 2022; Smadi et al. 2022). This approach is expected to reduce CO_2 emissions originating from burning fossil fuels (40%). It is also expected to make CO_2 capture after calcination much more economical, as it only requires the condensation of steam and collection of CO_2. This steam can then be recycled and reused. Essentially, renewable electricity drives calcination, and the stored hydrogen can be used when renewables are unavailable. This technology is still at TRL 3 but appears to be promising.

In Saudi Arabia, the availability of subsided fossil-based low-cost fuels such as heavy fuel oil makes using alternative fuels, especially hydrogen, unlikely in the foreseeable future. This is because there are more cost-effective alternative routes for decarbonizing the cement industry. The most cost-effective measure in the short term is clinker substitution, followed by using waste, particularly biomass, and low-carbon waste, which can be implemented rapidly, as the technology is mature and retrofitting into existing kilns is inexpensive. Carbon capture is unlikely to be viable in the near future at the current cost of capture ($100 per tonne of CO_2), transport, and storage. However, it could be used as an interim measure to reduce CO_2 intensity if the regulatory framework changes, new niche export markets emerge, or government incentives are offered.

Aluminum industry

While aluminum production is energy-intensive, the Ma'aden plant is relatively new, and major investment in alternative fuels may not be a viable option in the short term without the influence of external factors such as niche markets (green metals), carbon pricing, or government incentives. Hydrogen utilization in aluminum production can be through adopting the Bayer process, where combustion products are replaced with steam as the calcination medium, or firming the renewable power network if used. These two avenues are viable with minimal additional investment if decarbonization is on the agenda. In the interim, hydrogen blending into natural gas may help reduce CO_2 emissions but would not have any tangible impact due to the high emission intensity of the industry. Most existing combustion processes can accommodate up to 20% (by volume) hydrogen blended with natural gas without requiring any major changes to these systems.

In early June 2022, Ma'aden signed a memorandum of understanding with GlassPoint to build the world's largest solar thermal plant at the Ras al Khair refinery. The 1,500-megawatt facility will help Ma'aden achieve its sustainability goals by reducing carbon emissions by more than 600,000 tonnes annually (50% of the carbon footprint of the Alumina refinery) or 4% of its overall carbon footprint. The steam will be used to refine the bauxite ore to alumina. However, the contribution of the aluminum industry to CO_2 emissions in Saudi Arabia is estimated to be less than 0.2% at the current production rate.

Phosphate industry

The production of di-ammonium phosphate and mono-ammonium phosphate requires phosphate rock, ammonia, and sulfuric acid. Dried phosphate ore is most commonly processed into ammoniated phosphates by reacting phosphate rock with sulfuric acid to produce phosphoric acid. This phosphoric acid is then reacted with ammonia to produce ammoniated mono-ammonium phosphate or di-ammonium phosphate.

Hydrogen is clearly needed to produce ammonia, which can be manufactured from renewable sources. It is already integrated into the process and any additional integration of hydrogen may have to account for the thermal energy and power generated for the production of chemicals. The current plants at Ma'aden are well integrated and no immediate opportunities are identified. The only possible use of hydrogen beyond power is recycling gypsum, which is a byproduct of the production of mono-ammonium phosphate and di-ammonium phosphate. Gypsum recycling can use renewable energy and is supplemented with stored green or blue hydrogen.

Discussion

The above discussion identified ways in which hydrogen can be integrated and used in the four industries examined in this chapter. However, synergy is critical for the introduction of new fuels and processes into heavy industry. These industries have been optimized over the decades and any new process must be well integrated to maximize utilization and return on investment. The scale of these industries and amount of hydrogen needed will mean that hydrogen production must occur close to major industrial hubs for it to be viable. This is not only due to the cost associated with transport and storage but also due to the available infrastructure at these sites. Synergy is also likely due to the potential use of hydrogen owing to its versatility, as noted earlier in this chapter. For example, hydrogen can be used as a fuel for trucks and cars; as a backup for power generation; as a feedstock for ammonia, methanol, or ethylene glycol production; as a reductant of iron; and as an energy source for high-temperature processes.

This chapter also discusses the drivers and barriers for hydrogen utilization. There are four main drivers:

- Opportunities to modify current industrial processes that bring about efficiency gains can offset the additional cost associated with hydrogen use.
- Emerging markets for high-premium green products that will pay for low-carbon production.
- Capitalizing on existing trading routes and ensuring compliance with global trends in carbon reduction and business sustainability.
- Social responsibility, environmental obligations, and international standing.

The five main barriers are as follows:

- Cost of fuel production, transport, and storage.
- Supply chain and ramping up rate to meet market demand.
- CAPEX required for both retrofitting and green fields.
- Risk associated with scaling new technology.
- Long-term investment plans and certainty in governmental policy.

Considering the above, the following projections are made in terms of opportunities and investments needed at different horizons in the future. The near term (2030) will be primarily impacted by the Vision 2030 framework and its targets. There will be two major implications for heavy industry: reducing carbon emissions from the power sector and expanding the mineral industry. The first will be mostly achieved by switching from liquid fossil fuels to natural gas, supplemented by large-scale solar and wind installations. However, the expansion of the mineral industry is likely to increase CO_2 emissions if traditional fossil-based technology is used. Such an expansion may not have a major impact on emissions until the end of the decade.

In terms of hydrogen utilization and technological development within this period, it is projected that hydrogen blending will be required in heavy industry, especially for petrochemicals, iron, and steel. Remote power generation, especially in mines, may also consider adopting ammonia or hydrogen as a blend of existing gas turbines and engines. Finally, research, development, and small-scale demonstrations must continue, to allow the retrofitting of existing technology and processes to the use of hydrogen when it is economically viable and the supply chain is established.

When considering the intermediate time horizon (2040), hydrogen and ammonia penetration in the iron and steel industry is highly likely to be a component of firms' decarbonization plans. There will also be increased government pressure and a potential increase in demand for low-carbon steel. In this period, establishing transport and storage infrastructures for hydrogen could be crucial for industrial hubs, and reducing hydrogen costs could help increase adaptation plans. Further, hydrogen, as an energy storage vector at a small scale, in the niche industry and at remote locations could become cost-effective.

Using hydrogen for mobility, especially in remote areas, could also be viable once the technology has matured and hydrogen is locally supplied. However, further investment in the research and development of new technologies to use hydrogen, especially in processes that still rely on carbon-intensive fuels, is necessary.

By 2050, the increased hydrogen supply, both blue and green, will likely drive down prices and make its adaptation to various industries more viable. All four of the examined industries are expected to have integrated hydrogen into their operations, both as a chemical and as a heat source. Further, hydrogen technology with fuel flexibility is expected to be mature and readily available for use in both heat generation and mineral reduction. Finally, the use of hydrogen and ammonia as backups in the power generation sector will become more common.

Future research avenues

Research and development on integrating hydrogen into heavy industry is occurring at an accelerated rate. Studies are examining retrofitting to use pure hydrogen or using hydrogen as an alternative fuel and redesigning the entire process to accommodate hydrogen as fuel or reductant. Figure 22.3 provides a snapshot of the state of the technology and R&D and demonstration needed to use pure hydrogen as a fuel in many industrial systems requiring high-temperature heat.

In the iron and steel industry, hydrogen is now being blended at a small scale. Adding hydrogen to fossil fuels can help reduce the carbon footprint through the DRI process, reheat furnaces, and firm renewable power networks when they become available. This technology has a high TRL and some of it is fully commercial already. Nonetheless, areas in which higher blends are desired and processes are sensitive to temperature range, thermal radiation, and pollutant emissions require further research and development. In the long term, new reduction technologies

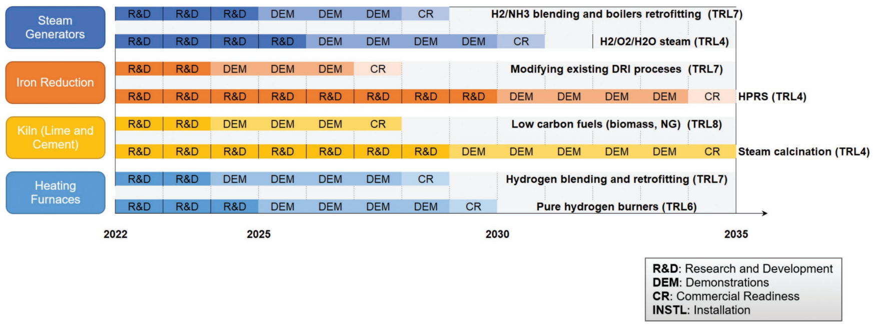

FIGURE 22.3 Timeline for the technological development of industrial equipment, showing the time required for research and development, modeling, demonstration, and commercial readiness. R&D – research and development, DEM – demonstration, CR – commercial readiness.

Source: Author.

such as hydrogen plasma smelting reduction (TRL 3 or 4) must be developed to reduce energy consumption and mitigate CO_2 emissions. Further, this development will open up the opportunity to using Saudi Arabia's low-grade ore without the need for an expensive beneficiation step.

In the lime and cement industries, hydrogen integration in the short term is limited because of the nature of the process and CO_2 emissions during calcination and clinkering processes. In the long term, steam calcination using a hydrogen/oxygen/steam mixture offers promise. Because this technology has a low TRL (3 or 4), academic institutions can collaborate with industry to develop this technology further and bring it to market in the next two decades.

In the aluminum industry, a similar approach to steam calcination can be adopted in the future, while hydrogen can also be used to generate heat. Academic research can then support the development of steam calcination and heat recovery as well as integration into renewable energy sources.

Finally, hydrogen is already used in the fertilizer industry and its further integration is relatively straightforward when it becomes financially viable. Gypsum recycling is another opportunity for hydrogen to play a role in collaboration with industry.

Case study

Hydrogen breakthrough ironmaking technology (HYBRIT)

HYBRIT is a joint venture between SSAB, LKAB, and Vattenfall that aims to replace coal with hydrogen in the steelmaking process. The HYBRIT system employs hydrogen produced using fossil-free electricity instead of coal and releases water instead of CO_2. The direct and indirect CO_2 emissions from producing a tonne of crude steel are estimated to be 1.83 tonne for a typical integrated steel plant. By contrast, the HYBRIT process, using hydrogen and renewable electricity, is expected to reduce these emissions to 25 kg of CO_2 per tonne of crude steel. Figure 22.4 shows the process, amount of energy required, and resulting CO_2 emissions.

Compared with the standard blast furnace/basic oxygen furnace process, HYBRIT reduces CO_2 per tonne of crude steel at the pelletizing plant by 40 kg because magnetite is oxidized into hematite during this process. This reaction releases heat, which replaces approximately two-thirds of the fossil fuel required when pellets are produced from hematite concentrate. In the HYBRT process, electrical furnaces and biofuels are used to produce green pellets. Most of the renewable electricity is used in hydrogen plants, where the electrolysis of water is used to generate green hydrogen. Hydrogen is used for the direct reduction process in a furnace. The off-gas of the reduction process is water, according to the simplified reaction: iron ore + hydrogen => iron + water. This results in solid porous sponge iron suitable for steelmaking. The electric arc furnace is then used for heating and melting

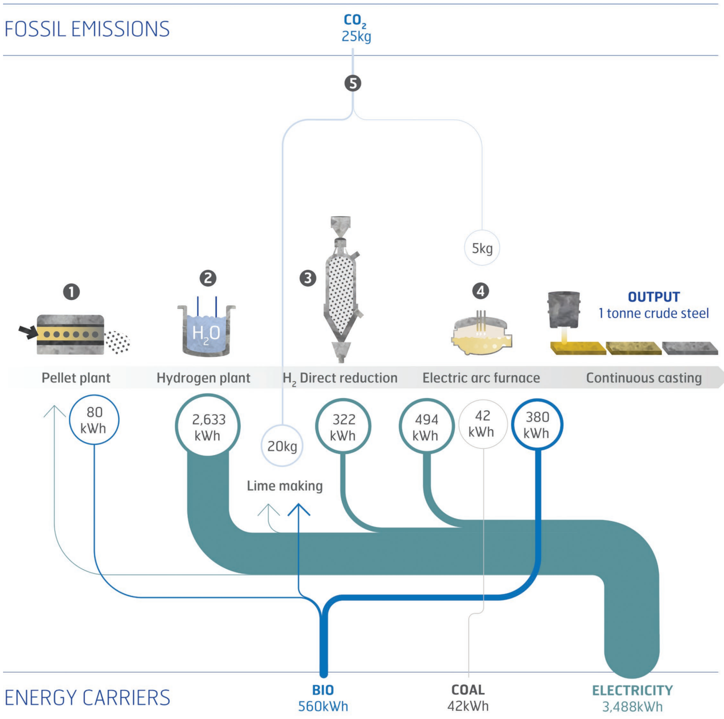

FIGURE 22.4 Schematic of the HYBRIT process showing the various steps and CO_2 emissions per tonne of crude steel.

Source: HYBRIT Brochure (2022).

charged materials using an electric current. The use of electric arc furnaces allows steel to be made from up to 100% scrap metal, or, as in the HYBRIT concept, from a mix of directly reduced iron and scrap. Similar to the current standard process, the liquid steel is tapped into a ladle where the final chemical composition and temperature of the steel are adjusted before they are cast into crude steel slabs in a continuous caster. Here, limestone, coal, and biofuels are added, which results in all the CO_2 emissions from the entire process. The CO_2 total shown is reduced dramatically, although minor emissions can still arise because of the use of certain process equipment and because small amounts of coal are still needed in the manufacturing process.

The HYBRIT project is in the pilot stage in northern Sweden, with full commercial-scale operations expected by 2026. Figure 22.5 highlights the various steps, scales, and activities since the project's inception in 2016. Assuming today's energy and commodities prices, the estimated cost of crude steel is expected to increase by 20%–30% under the HYBRIT technology compared with the blast furnace process. This additional cost is mostly related to the cost of energy (renewable

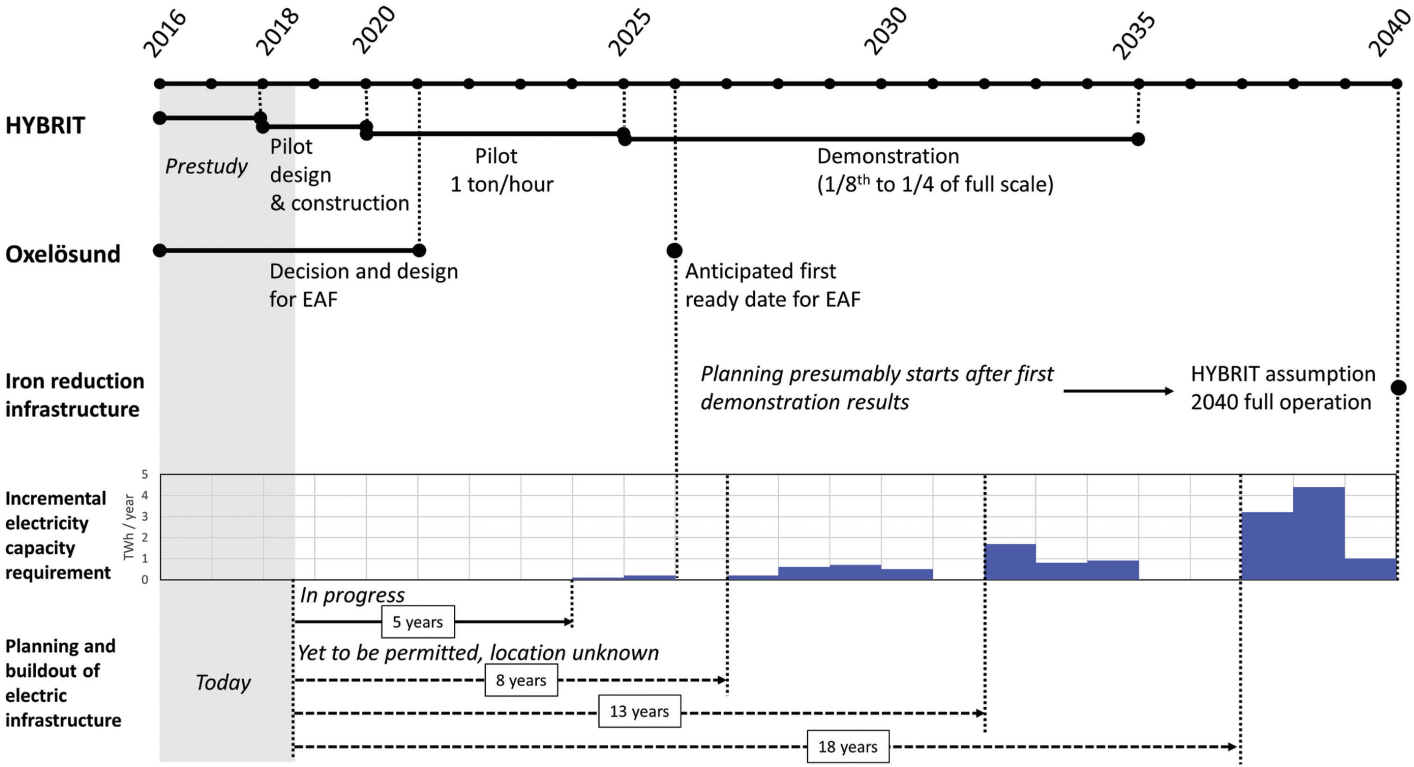

FIGURE 22.5 HYBRIT project timeline and activities.

Source: Kushnir et al. (2020).

hydrogen and electricity) and increase in capital expenditure. However, considering the predicted drop in the costs of both renewable energy and hydrogen, the HYBRIT process is expected to compete with current production methods.

Conclusion

This chapter discussed the potential and challenges of using hydrogen in heavy industry in Saudi Arabia. It covered four main industries: iron and steel, cement, aluminum, and phosphate. It reviewed the different technologies under which hydrogen can be used and described the potential pathways and strategies in the short, medium, and long term. In the short term (i.e., by 2030), the research, development, and small-scale demonstration of hydrogen blending are needed to allow integration into existing energy systems and processes, mostly in the steel, aluminum, and fertilizer industries. While no more than 20% (by volume) of hydrogen is expected to be added to fossil fuels, such an approach will nonetheless help prepare the required infrastructure, develop safety procedures, and achieve short-term reduction targets. The implementation of such a strategy is unlikely to be financially viable without a carbon tax, government subsidies, and/or strong demand for low-carbon minerals. Another opportunity relates to remote power generation, particularly in mines in which hydrogen and ammonia can be blended with diesel and natural gas in existing gas turbines and engines.

In the medium term (i.e., by 2040), demand for low-carbon metals is forecast to increase. At the same time, both blue and green hydrogen supply and infrastructure are expected to be developed. For iron and steel, DRI processes will need to be modified to accommodate a higher percentage of hydrogen, and heating burners will be retrofitted to accommodate hydrogen as a fuel. Hydrogen, as an energy storage vector at a small scale, niche industry, and at remote locations, is also likely to be used. Hydrogen for mobility in remote areas could also be viable once the technology has matured and hydrogen is locally supplied. Further investment in the research and development of new technologies to use hydrogen will be needed, as the industry looks to decarbonize its operations, particularly technology for carbon-free steam calcination for limestone, cement, and bauxite; hydrogen-DRI for iron reduction; and the production of synthetic fuels from captured CO_2.

In the long term (i.e., by 2050), the increased hydrogen supply, both blue and green, will likely drive down the price and make its adaptation to various industries more viable. By 2050, hydrogen technology is expected to be mature and readily available for use in both heat generation and mineral reduction. Hydrogen and ammonia use as backups in the power generation sector will also become more common and opportunities for green chemicals such as methanol and aviation fuel may become financially viable. However, further research and development will still be necessary to continue one-step iron reduction, increase the recycling of metals, and adopt innovative processes that can replace current fossil fuel-based technologies.

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23

THE POTENTIAL OF HYDROGEN INTERNAL COMBUSTION ENGINES FOR HEAVY-DUTY APPLICATIONS

James W. Turner, Sebastian Verhelst and Manuel E. Marquez

Introduction

The importance of fast charging and high on-board energy storage capability

In a decarbonized future in which vehicles' carbon dioxide (CO_2) emissions are heavily constrained, hydrogen offers a direct solution to the problem of such emissions at point of use. Furthermore, compared with other major technologies proposed for land transport, namely, battery electric vehicles (BEVs), hydrogen vehicles can be rapidly recharged as well as configured so that more energy can be carried. The magnitude of the latter advantage is such that the higher inefficiency of the powertrain can be overcome to a significant degree, thereby extending the driving range. These two capabilities mean that vehicles using hydrogen as their primary energy storage medium may be superior to BEVs, particularly for heavy-duty (HD) applications.

Various hydrogen storage technologies exist, including physical and chemical. Chemical storage technologies have not yet been shown to be truly practical for vehicular use (and are not discussed further here). Meanwhile, physical storage technologies are the most advanced type. The two most commonly used technologies are pressurized and liquid storage. For pressurized gas applications, two storage pressures are commonly used: 350 bar and 700 bar. First, 700 bar is used by systems producing light-duty (LD) vehicles, including the systems of Toyota, Hyundai, and Honda. Second, 350 bar is used for HD applications, as the system volume is less challenging for trucks. Additionally, compression energy is saved by not having to double the pressure (Weber 2022). For example, BMW successfully trialed liquid hydrogen tank systems and developed a production process for them in collaboration with Magna Steyr (Amaseder and Krainz 2006).

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Without specifying which approach should be used, the US Department of Energy (DOE) has targeted an infrastructure-to-vehicle transfer rate of 5 kg of hydrogen in 2.5 minutes (i.e., 2 kg/min; US Department of Energy 2021). This value equates to a charging rate of 4 MW or 67 kWh/min (Turner 2020). This represents an energy transfer rate nearly six times that presently rolled out for BEV charging (e.g., 350 kW by Porsche). However, importantly, no thermal management issues exist under this approach. Such issues usually arise from the fact that battery charging efficiencies are typically 95% and that an electric system would simultaneously have to dissipate 17.5 kW of heat at a charging rate of 350 kW. In addition to these two commonly known physical storage methods, cryo-compressed storage offers twice the hydrogen density of 700-bar compressed storage and concomitantly the potential for very high energy transfer rates. Brunner and Kircher (2016) stated that BMW achieved transfer rates of 2 kg/min in 2012 by using cryo-compressed gas storage, equaling the then-long-term US DOE target (see Figure 29.7, page 9 of Brunner and Kircher 2016).

High energy transfer rates can help address the second point to some extent by overcoming the efficiency disadvantage all powertrain concepts suffer compared with pure electric propulsion. While the energy transfer rate differs from energy density, the ability to transfer energy quickly allows greater vehicle utilization; this is important for commercial applications, especially HD applications. To reinforce this, compare the charging inefficiency of a battery with that of chemical energy transfer. Filling any tank when fugitive emissions are absent is a 100% efficient process, as is its discharge process. However, as mentioned above, batteries suffer from significant charging losses as well as losses on discharge, both of which must be thermally managed and represent an erosion of the useful energy transferred.

Hence, when the refueling rate is important, the attraction of hydrogen over electricity as an energy storage medium is clear. However, hydrogen also has an advantage in terms of the amount of energy that can be stored in a given vehicle platform, although this depends on the amount of energy to be carried. Regarding the automotive sector, Pearson, Turner, and Peck (2009) compared the capability of various energy vectors when the mass or volume of the entire energy storage system is included. In this setting, 700-bar pressurized hydrogen is about 10 times better than Li-ion batteries on a gravimetric basis and about 2.5 times better in volumetric terms. The corresponding values for liquid hydrogen storage are 10 and 5 times, respectively. This calculation was based on LD requirements. However, the advantage of hydrogen increases for applications necessitating a greater energy storage capability such as long-distance HD vehicular use. This is because battery mass and volume linearly follow the amount of energy stored, whereas the mass of a torispherical hydrogen tank system with a constant wall thickness is *not* linearly dependent on the mass of gas contained. For this reason, liquid hydrogen has traditionally been the fuel of choice for larger rocket applications. Specifically, hydrogen's very high lower heating value becomes an increasingly major benefit over hydrocarbon fuels as the proportion of mass attributable to the tank system reduces.

This overview suggests that hydrogen is expected to play a major role in long-distance transport, as the physical advantages of its greater energy storage capability and more rapid refueling surpass those of BEVs for zero-tailpipe-CO_2 emission propulsion. This provides the energy efficiency advantage of electric propulsion can be mitigated at the system level.

The remainder of this chapter discusses this point in greater detail. Using thermal conversion via combustion in engines versus electrochemical conversion in fuel cells (FCs) is first discussed.

An alternative to FCs in the chemical energy conversion of hydrogen

In this section, we compare the internal combustion engine (ICE) with the FC type most commonly proposed for automotive applications, namely, the proton exchange membrane (PEM) cell. Here, we do not examine solid oxide fuel cells (SOFCs), as we limit our discussion to more near-term possibilities. SOFCs, which can reach very high efficiencies when compounded by a gas turbine (GT; Azizi and Brouwer 2018), have been discussed in the context of larger applications, and the solid oxide fuel cell-gas turbine (SOFC–GT) hybrid system has even been analyzed for aeronautical use (Collins and McLarty 2020).

The chemical energy stored in the bonds of molecules can be liberated via two main pathways. One pathway is their combustion to release heat, which is then converted to work in an engine. Another pathway is electrochemically in an FC. Practically, the types of fuel energy converters in both ICEs and external combustion engines require oxygen to react the fuel with, which is conventionally sourced from the atmosphere. However, for brevity, only the ICE type is discussed here.

ICEs have a vast manufacturing infrastructure. Their cost-effectiveness, combined with the historical use of liquid hydrocarbon fuels, has ensured their position as the dominant prime mover for a wide range of power requirements. This is despite their relative immaturity compared with batteries and FCs, both of which significantly predate them. Nevertheless, they have two major disadvantages compared with FCs and batteries. First, because they convert thermal energy, they are subject to the limitation of Carnot cycle efficiency. This states that the maximum efficiency obtained from such a thermal system depends on the maximum and minimum cycle temperatures, as shown in Equation (1):

$$\eta_{Carnot} = 1 - \frac{T_{Low}}{T_{High}}$$

where η_{Carnot} is the Carnot cycle efficiency, T_{High} is the maximum temperature in the cycle, and T_{Low} is the minimum temperature in the cycle.

Conversely, as electrochemical devices, both the FC and the battery are ostensibly *not* subject to this limitation. Nonetheless, the efficiency of any subsystem attached to them to facilitate their operation will be limited by the Carnot cycle efficiency if they depend on a temperature change. However, since these subsystems do not represent the bulk of the energy flow, they have minimal effect on the efficiency of the entire system. Hence, the ICE, where all the energy is converted thermally, is immediately at a significant disadvantage thermodynamically.

Second, the combustion of fuels with oxygen is a high-temperature process (referring to Equation (1), arguably, the higher the better considering the Carnot limitation). This can give rise to nitrogen oxide (NOx) emissions. For hydrocarbon fuels, we must also consider unburned hydrocarbons, carbon monoxide (CO), CO_2, and soot (or particulate matter) emissions. However, since these are non-carbonaceous, they are all theoretically eliminated with hydrogen (although the undesired combustion of lubricating oil must be avoided). Unfortunately, hydrogen has a very high adiabatic flame temperature, which exacerbates NOx formation. This leads to an operational challenge, albeit one for which solutions exist (see the later discussion on engine operating strategies). Neither batteries nor FCs suffer from such problems. In particular, FCs do not suffer from these problems because the mass transfer and molecular recombination occur via an electrode. This precludes the involvement of nitrogen in the process, and the temperatures involved are far lower than those in an engine combustion chamber.

In a future in which hydrogen is a major energy vector, ICEs may be assumed to be at an inherent disadvantage, but this is not necessarily the case. In addition to their cost advantage and the fact that they can be manufactured from abundant and readily recycled materials, ICEs have several other benefits. Owing to the method of energy conversion, the primary output of an engine involves mechanical work, whereas, similar to batteries, FCs only produce electricity and heat. The production of mechanical power output in turn means that more efficient transmissions can be used in vehicles, with or without electrical hybridization. Thus, at the system level, ICEs can begin to reverse the situation. Even in the case of older vehicle technologies in US mid-size cars, Rousseau et al. (2008) estimated that a hydrogen ICE could compete with a PEM FC in terms of fuel consumption. It is interesting to note that these estimations were based on engine and hybrid vehicle technology that was advanced then but of the norm now.

In the United States, Argonne National Laboratory found that the peak stack efficiency of a 2017 Toyota Mirai PEM FC vehicle was 66% (Lohse-Busch et al. 2018). By contrast, the peak system efficiency (i.e., fuel energy to electrical energy, accounting for air supply system losses) was 63.7% at the same loading (Lohse-Busch et al. 2018).[1] The latter value is extremely impressive compared with ICEs, where reaching 55% is a research goal for the production of HD engines. However, as these peak efficiencies occurred at 5%–10% peak power, several points must be made:

1. The efficiencies of FCs drop off monotonically beyond their peak. At a 100% load, stack efficiency reduces to 48% and FC system efficiency to below 40%. While the latter is still impressive at the 90 kW peak power level produced by the Mirai FC, it is not significantly better than that of many diesel ICEs.
2. The peak efficiency for ICEs is 40%–50% of maximum power.

3 For FCs, tank-to-wheel efficiency falls significantly under the requirement for an electric-only transmission. If such a transmission were 90%–95% efficient, tank-to-wheel efficiency at maximum power would then be 36%–38%. This is an important point when considering HD applications, which habitually operate at a much higher proportion of full load.
4 A parallel hybrid transmission can readily be employed with ICEs. Not only is the engine's highest efficiency in a more useful area of the map, but a hybrid transmission can also help raise it.

Reporting for the US DOE, Kurtz et al. (2017) stated that system efficiencies are generally around 57% at one-quarter power, whereas this drops to 43% at peak power (see also Lohse-Busch et al. 2018). In 2021, Toyota launched a new Mirai, and the efficiency of its FC is claimed to be higher. For optimized HD applications, tailoring the FC efficiency curve would benefit its use in that application. However, for engines, efficiency rapidly increases with size, primarily because of reduced thermal losses and reduced friction owing to the necessary lower rotational speeds. This effect is particularly true when moving from road-going LD to HD applications. Finally, because of their high exhaust temperatures, ICEs have significant further potential in waste heat recovery, whereas there is virtually no such opportunity for PEM FCs. However, this is not the case for SOFCs, which are higher-temperature devices than PEMs, as discussed in the subsection titled "The SOFC–GT engine."

The foregoing shows that for HD vehicles in which the engines are generally larger, hybridized ICEs should have an opportunity to compete with FCs on an energy-efficiency basis. This is already the case for hydrocarbon fuels, but further opportunities exist when optimized hydrogen use in ICEs is considered, as is now discussed.

Research on using hydrogen as a fuel for automotive ICEs

Verhelst and Wallner (2009), Verhelst (2013), and Yip et al. (2019) provided excellent overviews of the use of hydrogen in ICEs, explaining the challenges, applications, and research gaps. In an earlier paper, Das (1990) stated that the first commercial application of hydrogen in transport was in the 1930s, predating when ammonia was first used for transport purposes (Valera-Medina et al. 2018). Ammonia is mentioned here because it is another non-carbonaceous energy carrier that can be synthesized from renewable energy and is considered to be a potential hydrogen carrier. However, it is not discussed further because while it may have some storage advantages, it is a noxious and poisonous gas and its combustion characteristics are worse than those of hydrogen.

Characteristics of hydrogen in engine applications

Hydrogen is a more interesting fuel than common hydrocarbon alternatives for many reasons. These include its very high laminar burning velocity (LBV) and very wide flammability limits, which range from 4% to 77% by volume in air.

Given these limits and its extremely low ignition energy, hydrogen is extremely hazardous, and significant precautions must be taken when using it (Verhelst and Wallner 2009). As a fuel, its characteristics provide both opportunities and challenges in typical ICE systems (see Tables 23.1 and 23.2) compared with methane and iso-octane. Methane is considered to be representative of a gaseous fuel, while iso-octane represents a typical liquid hydrocarbon fuel.

The LBV of hydrogen is approximately six times higher than that of typical hydrocarbons. At its stoichiometric air/fuel ratio is 34.08, its combustion is shorter than that of gasoline by a factor of approximately 2.5. Its very high LBV also means that its dilution tolerance is very high, allowing very lean combustion. Eichlseder et al. (2003) stated that operation is possible at $\lambda = 10.5$, which corresponds to the lean combustion limit. Conversely, the rich limit is $\lambda = 0.125$. As a consequence of the ease of operation beyond $\lambda = 4$, mixture quality control is possible over most of the engine operating map, although some throttling may be necessary at very light loads to stay within acceptable combustion stability limits. Throttling is also typically necessary for the so-called lambda leap to control NOx (see the later discussion on engine operating strategies). With respect to full-load operation, the extremely low density of hydrogen displaces significant quantities of air (29.6% at stoichiometry). While this concomitantly reduces power output in naturally aspirated engines with external mixture preparation, it serves as part of the ability to control load through mixture quality.

The disadvantages of hydrogen in spark ignition (SI) engine operation include its very short flame quenching distance, which means that heat transfer to the engine structure is greater in homogeneous combustion systems. This not only reduces

TABLE 23.1 Properties of hydrogen compared with methane and iso-octane.

Property	*Hydrogen*	*Methane*	*Iso-octane*
Molecular weight (g/mol)	2.016	16.043	114.236
Density (kg/m^3)	0.08	0.65	692
Mass diffusivity in air (cm^2/s)	0.61	0.16	~0.07
Minimum ignition energy (mJ)	0.02	0.28	0.28
Minimum quenching distance (mm)	0.64	2.03	3.5
Flammability limits in air (vol%)	4–75	5–15	1.1–6
Flammability limits (λ)	10–0.14	2–0.6	1.51–0.26
Flammability limits (ϕ)	0.1–7.1	0.5–1.67	0.66–3.85
Lower heating value (MJ/kg)	120	50	44.3
Higher heating value (MJ/kg)	142	55.5	47.8
Stoichiometric air-to-fuel ratio (kg/kg)	34.2	17.1	15.0
Stoichiometric air-to-fuel ratio (kmol/kmol)	2.387	9.547	59.666
Specific heat at constant pressure (MJ/kgK)	14.307	2.2537	1.7113
Gas constant R (kJ/kgK)	4.124	0.5182	0.0729
Ratio of specific heats γ	1.405	1.299	1.044

Source: Verhelst and Wallner (2009), with additional data from Ohio University (2021).

Data given at 300 K and 1 atm.

TABLE 23.2 Properties of hydrogen/air, methane/air, and iso-octane/air mixtures.

Property	*H2/air* *(λ = 1, ϕ = 1)*	*H2/air* *(λ = 4, ϕ = 0.25)*	*CH4/air* *(λ = 1, ϕ = 1)*	*C8H18/air* *(λ = 1, ϕ = 1)*
Volume fraction fuel (%)	29.5	9.5	9.5	1.65
Mixture density (kg/m^3)	0.850	1.068	1.123	1.229
Kinematic viscosity (mm^2/s)	21.6	17.4	16	15.2
Autoignition temperature (K)	858	>858	813	690
Adiabatic flame temperature (K)	2390	1061	2226	2276
Thermal conductivity (10^{-2} W/mK)	4.97	3.17	2.42	2.36
Thermal diffusivity (mm^2/s)	42.1	26.8	20.1	18.3
Ratio of specific heats	1.401	1.400	1.354	1.389
Speed of sound (m/s)	408.6	364.3	353.9	334.0
Air-to-fuel ratio (kg/kg)	34.2	136.6	17.1	15.1
Mole ratio before/after combustion	0.86	0.95	1.01	1.07
LBV, ~360 K (cm/s)	290	12	48	45
Gravimetric energy content (kJ/kg)	3758	959	3028	3013
Volumetric energy content (kJ/m^3)	3189	1024	3041	3704

Source: Verhelst and Wallner (2009).

Data given at 300 K and 1 atm (with the exception of the LBV, given at 360 K and 1 atm).

efficiency but also increases thermomechanical stresses. Stratified or diesel-type mixing control can address this. Further, owing to the very low ignition energy, preignition (PI) and backfire have historically been problematic, particularly with external mixture preparation, although means of addressing this have been devised (see the next section). Verhelst, Sierens, and Verstraeten (2006) discussed the conflation of knocking behavior with PI for hydrogen, deducing that while its octane numbers, particularly its research octane number, may be high, PI obscures the truth in many cases.

The following sections discuss how these fuel characteristics are pertinent to work investigating the use of hydrogen as a fuel in engines.

Engine performance and operating strategies with port-fuel injection (PFI; external mixture preparation)

BMW has long researched the SI of hydrogen/air mixtures, and its PFI research program resulted in a limited-production vehicle employing a bi-fuel approach, the BMW Hydrogen 7 (based on the then-current 760iL mass production model).

One hundred of these vehicles were produced between 2005 and 2007 (Wikipedia 2021). This bi-fuel vehicle, which used a 6.0-liter V12 engine with two separate fuel systems, was designed to offer the same performance when operating on gasoline or hydrogen (Kiesgen et al. 2006). While the gasoline fuel system used direct injection (DI), the hydrogen fuel system used PFI. Liquid hydrogen was stored in a cryogenic tank in the boot of the vehicle, which was developed to production-ready status (Amaseder and Krainz 2006).

Much of the historical literature on the application of hydrogen in SI combustion systems comes from BMW's extended research program and the Technical University of Graz. Freymann, Pehr, and Strobl (2002) discussed BMW's early work. Given the improvement in combustion because of the fast LBV and high knock resistance, Eichlseder et al. (2003) stated that external mixture preparation hydrogen engines generally have a maximum power capability of approximately 80% that of gasoline despite the high level of oxygen displacement. However, this disadvantage is offset by the ability to control load using mixture quality, thereby reducing filling time markedly. The V12 engine in the Hydrogen 7 vehicle also used BMW's Valvetronic mechanically variable valve timing system to control load. While this was necessary for gasoline operation, it was only used at part load with hydrogen and to facilitate changing operation between fuels. Within this engine, operating on hydrogen necessitated reducing the compression ratio (CR) from the standard production value of 11.3–9.5 due to abnormal combustion as well as using calibration strategies to minimize NOx emissions. Owing to the very fast combustion rates and desire to run at maximum efficiency, the CR may have been reduced to limit the peak cylinder pressure seen during operation.

These very fast combustion rates mean that if knock and PI can be avoided, optimal ignition timings are very close to top dead center, provided peak cylinder pressure limits are not exceeded. Regarding the Hydrogen 7, Kiesgen et al. (2006) stated that when using hydrogen at full load, the optimal ignition timing was only 1° before top dead center. This reflects the observation regarding the combustion duration above, which is partly responsible for the fact that the power output for a PFI hydrogen engine is more than the oxygen displacement would lead one to expect.

Tang et al. (2002), who discussed the problem of PI, backfire, and knock, operated Ford Motor Company's PFI hydrogen engine with three satisfactory CRs up to 15.3. Generally, very lean equivalence ratios had to be used to limit backfire, together with a reduction in valve overlap because the incoming fresh charge is essentially ignited by concentrations of hot residuals in the combustion chamber. This is a significant disadvantage of external mixture preparation, which the BMW Hydrogen 7 engine mitigated by using its Valvetronic system. This approach limited both valve overlap and intake depression, thereby minimizing residual retention and showing that modern variable valve systems can help significantly. Nevertheless, the introduction of hydrogen into the intake runner in the BMW engine also had to be optimized to stop fresh hydrogen passing through on overlap, as discussed by Kiesgen et al. (2006). Tang et al. (2002) reported brake thermal efficiencies (BTEs) of around 38% despite operating lean. Conversely, the valve train of the BMW engine enabled stoichiometric operation. However, the highest efficiency was around that reported by the Ford researchers (Eichlseder et al. 2003). The use of the stoichiometric air/fuel ratio was important for full-load exhaust after treatment (EAT), as discussed under the subsection titled "Emissions control." The peak BTE reported by Tang et al. (2002) is similar to what a conventional SI engine operating on gasoline using DI would be expected to achieve. However, SI engines following Miller cycle strategies would be expected to be more efficient.

Not all ICE research in this area has been conducted with reciprocating engines: several Wankel rotary engines have been operated on hydrogen. However, the Wankel design is peculiar in that its operating cycle is laid out sequentially around the housing. Hence, the definition of external and internal mixture preparation becomes somewhat blurred, and this engine type is discussed separately in the section on the Wankel engine.

In summary, reciprocating four-stroke engines employing external hydrogen mixture preparation are severely handicapped by PI and backfire. Indeed, either lean operation at full load or extra complications in the valve train must be employed. Knock is arguably less of a restriction, although these two main forms of abnormal combustion have not yet been definitively separated. The BTEs achieved with this mixture preparation method are no longer acceptable even for LD engines operating on gasoline. This is definitely the case for HD vehicles, where competition with FCs is likely to be strong in the future. Many of the limitations of external mixture preparation can be eliminated using hydrogen DI. This enables different operating strategies and greater operational flexibility, as discussed in the next section.

Engine performance and operating strategies with DI (internal mixture preparation)

Several research groups have published content on hydrogen DI combustion systems. This mixture preparation approach eliminates backfire since hydrogen is not introduced into the working chamber until after the exhaust valves have closed. Moreover, the hot residuals are diluted by fresh air through the homogenization of the in-cylinder temperature. Furthermore, higher specific outputs can be achieved when the hydrogen introduction is delayed until after closing the intake valves (17% higher than gasoline for naturally aspirated engines; Wimmer et al. 2005). However, injecting when the intake valves are still open enables a degree of dethrottling as well. All these strategies have been disclosed and discussed by the BMW–Graz research group since 2003 (Eichlseder et al. 2003; Rottengruber et al. 2004; Wimmer et al. 2005).

Increasing BTEs was a driver of this research. With DI, higher CRs are permitted because of the delayed introduction of hydrogen. Wimmer and Gerbig (2006) showed that in conjunction with stratification, raising the CR to 16–18 should allow a hydrogen DI SI engine to rival the efficiency of a diesel engine (providing heat rejection can be reduced as well). Eichlseder et al. (2003) showed that a 50% BTE should be achievable with such an engine. They also stated that this would rival an FC in vehicles (at the time the article was published). They showed that part of this higher efficiency with DI comes from delaying the hydrogen introduction as much as possible. As shown in Table 23.1, this reduces the increase in compression work resulting from the significantly higher constant pressure of hydrogen compared with air (the value of hydrogen is 14.23 times that of air). Operationally, this delay in the fuel introduction is permitted by the very high diffusivity of hydrogen in air. Wimmer et al. (2005) reinforced the findings of Eichlseder et al. (2003) in this respect.

Interestingly, under high diffusivity, the DI of hydrogen appears to be relatively insensitive to injector targeting. Rottengruber et al. (2004) investigated different numbers of holes in a direct injector. Even one hole was shown to work well in homogeneous operation, indicating the magnitude of the diffusivity mentioned earlier. They also investigated the effect of reducing injection pressure from 150 bar (their default setting) to 45 bar. Important combustion metrics such as the position of the 50% mass fraction burned and the coefficient of variation of the indicated mean effective pressure were constant across this range and efficiency declined only slightly. This reduction could be due to the increased compression work resulting from the longer injection periods necessary to introduce the same amount of hydrogen and its high constant pressure, as discussed above. Being able to operate at a lower injection pressure means that more of the volume of a pressurized tank can be used and “limp-home” strategies are possible below the “normal” minimum tank (i.e., injection) pressure.

Later work by the University of Michigan and Ford also investigated the effect of injection timing on compression work. Further, it discussed the fact that pneumatic work is recovered with late injection timings (i.e., the gas does not expand into a lower-pressure cylinder only to have to be compressed again). Younkins, Boyer, and Wooldridge (2013) estimated how much of the 110-bar injection pressure they used could be recovered. However, they also discussed the extent to which injection timing influences the significant trade-off between stratification, NOx emissions, and heat losses. These aspects are crucial for maintaining efficiency when operating on hydrogen. If injection is delayed, most of the fuel can be combusted in a relatively rich kernel around the spark plug, reducing the heat rejection because of the very lean areas near the walls. However, this brings more of the mixture volume into high-NOx-generating regions (see the subsection titled “Emissions control”). Throughout their work, they operated at $\phi = 0.4$ to limit NOx (this being $\lambda = 2.5$, the equivalence ratio, ϕ, being the reciprocal of λ). Nonetheless, they still achieved a 47.7% indicated thermal efficiency with the second iteration of their engine that used an unusual combustion system featuring a central injector and two side-mounted spark plugs. This was markedly different from BMW’s typical approach, which was to close-couple the injector and spark plug in the center of the combustion chamber, as is now common in its gasoline DI systems. The earlier version of the Ford engine of Younkins, Boyer, and Wooldridge (2013) used the close-coupled approach and provided an indicated thermal efficiency above 46.5%.

The cylinder head layout of the earlier version of Younkins, Boyer, and Wooldridge's engine had been used by researchers at the Argonne National Laboratory. By correcting for single-cylinder friction, these researchers had achieved a maximum BTE of 45.5% and a BTE above 35% across 80% of their tested range (Matthias, Wallner, and Scarcelli 2012). The Argonne engine had a longer stroke than that of Younkins, Boyer, and Wooldridge's (2013) engine, which, using the same cylinder head, resulted in a higher CR and better surface area-to-volume ratio (SVR), presumably helping account for its higher BTEs. Thus, the Argonne engine exceeded the DOE's targets for LD hydrogen engines (Matthias, Wallner, and Scarcelli 2012). These results suggest that as hydrogen DI/SI combustion systems develop, BMW's 50% BTE target may be realistic if operations at higher CRs can also be achieved.

More recently, researchers at Bosch and TU Graz have published results based on a simple conversion of an SI engine in which they replaced the gasoline DI system with a prototype hydrogen one (Seboldt et al. 2021). This research engine also had PFI; however, when operating on DI, it yielded the highest BTE of 39%, which, with a relatively low CR of 9.8, is above that expected of an engine of this specification operating on gasoline. Furthermore, the coefficient of variation of the indicated mean effective pressure was excellent across the map, as was the combustion phasing. This work suggests that existing engines could be simply converted to operate on hydrogen, with the uptake of such engines then leading to more optimized ones.

Given that BTEs of 45%–50% are possible for LD engines, higher efficiencies should be possible for HD engines owing to their potential for lower heat losses (due to a better SVR). However, stratification will be required, and knock will likely become increasingly problematic with larger bore sizes. Hence, moving to the mixing-controlled combustion of hydrogen in a diesel-type constant pressure combustion system would be advantageous. While Yip et al. (2019) discussed this, the ignition of the plumes can only practically be achieved using a diesel pilot injection, as discussed earlier. The need for technology that allows the use of monovalent diffusion-burning combustion systems is discussed in the section titled "Research gaps and opportunities." With the excellent results in SI combustion systems, however, in-vehicle efficiencies for HD hydrogen engines that rival PEM FCs should be possible (see the next section). This is especially since these diesel-type combustion systems can be produced and post-treatment issues can be resolved (see the subsection titled "Emissions control").

Case study: hydrogen as a fuel for HD trucks

Hydrogen represents a major opportunity for ICEs, with this technology reaching a 47% BTE for HD applications (Mayr et al. 2021). The higher efficiency for hydrogen ICEs is comparable with that of other emerging technologies such as

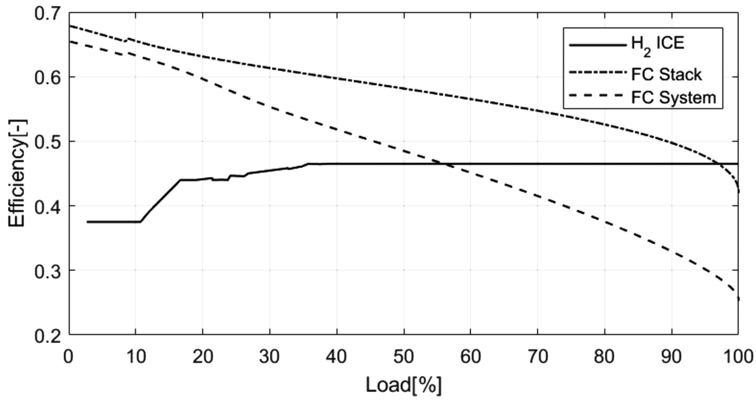

FIGURE 23.1 Hydrogen ICE, FC stack, and system efficiency for a HD truck.

Source: Authors.

FC powertrains. Recent studies of FCs have focused on automotive applications. These energy systems have shown potential efficiencies up to 60% (Lohse-Busch et al. 2018), and some vehicle manufacturers have built and tested working prototypes, including LD applications (e.g., Toyota Mirai) and HD road applications (e.g., XCIENT from Hyundai). Although FCs have high efficiency, their efficiency is highly dependent on load, decreasing by up to 30% at full load (including system auxiliaries such as pumps and compressors), as shown in Figure 23.1. By contrast, ICEs have high and almost constant efficiency at high loads, suggesting great potential for HD applications. Next, two powertrains, ICEs and FCs, are compared for an HD truck.

A full vehicle model is built for each powertrain (see Figure 23.2), and then the two are compared under real driving conditions, following a standard driving cycle for HD trucks. The full vehicle model used as a reference for the study is the Volvo FH4 truck in a 4 × 2 traction configuration with a load weight of 35,000 kg, as reported in Table 23.3. This model also includes a driver block to replicate the action of a real driver and follow the desired driving cycle. The FC model is based on a solid polymer electrolyte FC connected to a battery pack and then to a motor/generator to drive the truck. By contrast, the ICE powertrain is based on a series hybrid configuration. The ICE is attached to a generator connected to the battery pack, which finally powers the truck through a traction motor.

The FC model in this simulation is based on the solid polymer electrolyte FC reported by Lohse-Busch et al. (2018). This FC has 370 cells in the stack, reaching a maximum power of 114 kW, equal to the number in some HD prototypes (XCIENT from Hyundai; Linderl et al. 2021). On this scale, the fuel weighs around 100 kg and has a volume of 70 liters. The air and hydrogen supplies are modeled as a constant pressure source and the power consumption of the auxiliaries is modeled as a linear proportion of the electrical power consumption. The FC system is

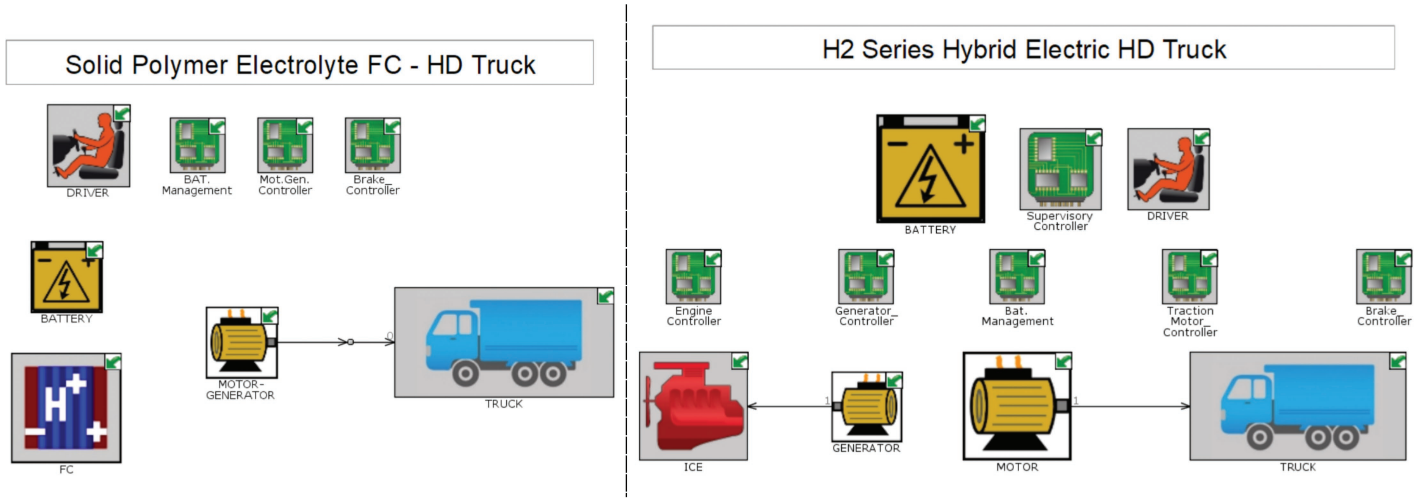

FIGURE 23.2 Simulation models: (left) FC powertrain, (right) hydrogen ICE series hybrid powertrain.

Source: Authors.

TABLE 23.3 Properties of the main simulation blocks for the two powertrains

Truck	
Reference	Volvo FH4
Drag coefficient	0.31 (–)
Traction	4 × 2
Load weight	35,000 (kg)
Battery	
Configuration	190 in series and 4 in parallel
Open circuit voltage	660 (V)
Capacity	400 (Ah)
Storage energy	263 (kWh) 950 (MJ)
Generator/Motor	
Max. power	210 (kW)
ICE	
Max. power	350 (kW)
Max. efficiency	46.5 (%)
Engine speed range	800–1,600 (rpm)
FC Stack	
Max. power	190 (kW)
Number of cells	620 (–)

connected to the battery pack with an open-circuit voltage of 660 V and a capacity of 400 Ah. Finally, a 210 kW electric motor receives the energy from the battery and drives the shaft of the truck.

By contrast, the ICE powertrain has a series hybrid configuration to improve the operating range of the engine efficiency. The ICE is a 13-liter engine running on hydrogen with a maximum output power of 350 kW (Mayr et al. 2021). This engine has a peak BTE of 47%, which is set as the operating region along with the whole operation of the powertrain. This reference engine uses the compression ignition principle coupled with a high-pressure DI system for hydrogen. Additionally, it may reduce NOx emissions by coupling with a customized post-treatment system. In this simulation model, the engine is coupled to an electric generator, which powers the battery pack. Then, the battery pack powers the traction motor that drives the truck. This aspect is the same as that of the FC powertrain for comparability purposes.

Both powertrains are tested under the same driving cycle to retain consistent conditions to improve comparability (see Figures 23.3 and 23.4). The selected driving cycle is the California HD cycle (Kasab and Strzelec 2020), which has a duration of 660 seconds and mixes low-load regions and high-load roads. This mixture allows us to compare the powertrains under large operating conditions, as shown by the power cycle in Figures 23.3 and 23.4. Additionally, the two simulation models aim to have a constant state of charge for the battery throughout the cycle, as shown in Figure 23.4. In these conditions, most fuel energy is

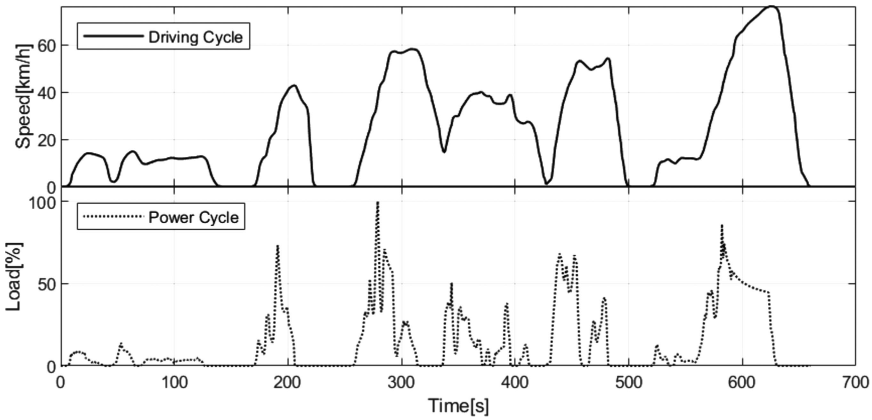

FIGURE 23.3 Driving and power cycles for the California HD legislation.

Source: Authors.

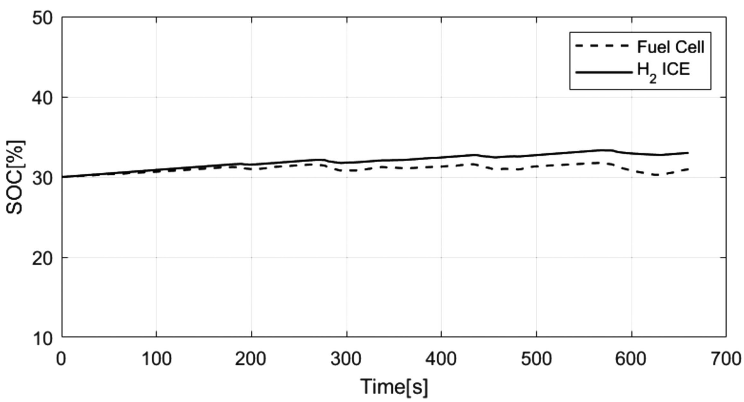

FIGURE 23.4 Battery's state of charge for the simulation of the two powertrains.

Source: Authors.

converted into traction energy on the truck, easing the energy flow and conversion in the two powertrains.

Figure 23.5 reports the efficiency of the powertrains. The ICE powertrain exhibits its higher efficiency than the FC powertrain. In this case, the simulated conditions with full load weight and constant state of charge (typical conditions for an HD fleet) represent a high-load condition for the powertrain. In the high-load region, the ICE has higher efficiency than FC powertrains with similar power requirement designs. A powertrain with an oversized FC (twice the reported power) could efficiently overcome the ICE powertrain. Nonetheless, from a technical and economic perspective, the size of FCs is incompatible with commercial purposes.

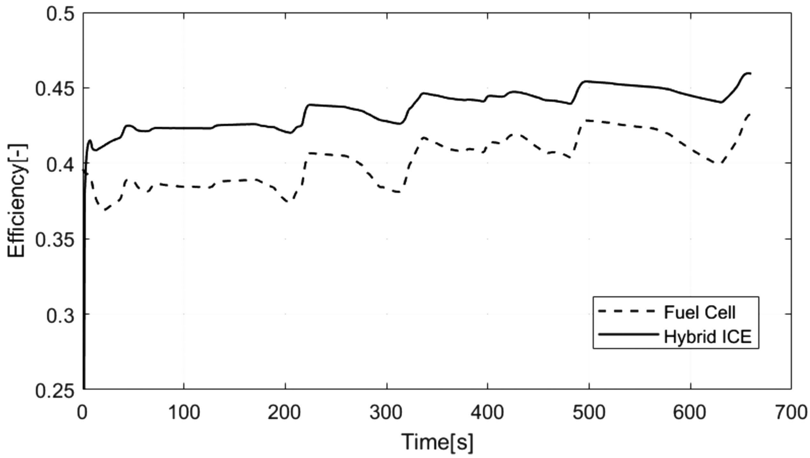

FIGURE 23.5 Powertrain efficiency throughout the California driving cycle.

Source: Authors.

Besides the higher efficiency in the high-load scenarios, ICEs have other benefits over FC powertrains. ICEs are considered to be a mature technology developed to the extent that they have low production prices and high reliability. By contrast, FCs still have some technical challenges to overcome before mass production, such as operating the cooling system of the powertrain at high loads. ICEs are also compatible with hybrid electric systems, which allow high-efficiency operation. One of the disadvantages of hydrogen ICEs is NOx emissions, which can be suppressed/controlled with the current technology, as discussed in more detail in the next section.

Emissions control

The ideal combustion of hydrogen would have no hydrocarbons, CO, or CO_2 emissions because no carbon would be involved in the combustion process. However, some combustion of the lubricating oil is likely. Fitting a catalyst suitable for stoichiometric operation could oxidize hydrocarbons and CO to water and CO_2 under all conditions assuming no rich mixture operation (i.e., lean to stoichiometric fueling only). Such a "three-way catalyst" (TWC), as termed in conventional gasoline combustion, could thus also be adopted for hydrogen engines. However, there would ideally be no emissions of two of the species such a catalyst usually converts. Because the oil consumption of modern engines is extremely low, original equipment manufacturers have had to address this issue to ensure emissions systems' compliance over extended mileages. Hence, we do not discuss hydrocarbons, CO, and CO_2 emissions further except to state that the EU intends to mandate a limit of 1 gCO_2/km for a vehicle to be considered a zero-emissions vehicle. Owing to the amount of energy such a vehicle consumes, this limit would be harder for an HD vehicle to meet than for an LD one. However, this issue is expected to be overcome using modern piston rings and cylinder design. Recent work led by Bosch and TU Graz proposed a full EAT suite, including a particulate filter to eliminate any soot emissions from hydrogen ICE vehicles (Kufferath et al. 2021).

Consequently, NOx emissions are a challenge for hydrogen combustion in air. This is because its adiabatic flame temperature is high and the engine is habitually operated lean for optimal fuel consumption, as discussed above. Verhelst and Wallner (2009) found that operation at leaner than $\lambda = 2.2$ produces negligible NOx because the flame speed reduces due to the presence of excess oxygen, as shown in Figure 23.6. Operating at $\lambda = 1.3$ produces maximum NOx, approximately 2.7 times higher than that produced at $\lambda = 1$. The increase in NOx just lean of stoichiometric is due to the competition between increasing oxygen availability for its formation and a reducing gas temperature. This situation is not resolved in favor of declining heat availability until $\lambda = 1.3$.

Eichlseder et al. (2003) described research investigating the limits of operation and NOx emissions control; meanwhile, Berckmüller et al. (2003) and Rottengruber et al. (2004) discussed mixture preparation and emissions control, including the use of exhaust gas recirculation (EGR), which we discuss later in this section.

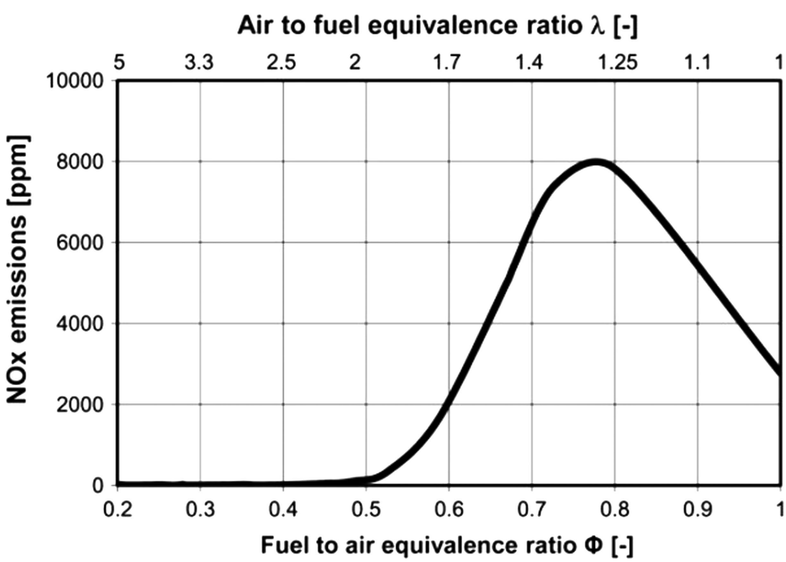

FIGURE 23.6 NOx emissions from hydrogen combustion in air compared with the air-fuel equivalence ratio λ and its reciprocal ϕ.

Source: Verhelst and Wallner 2009.

Stoichiometric operation permits the use of a TWC, which will itself not convert NOx in a lean gas stream, and near-zero NOx is emitted from the combustion chamber beyond $\lambda = 2.2$. Therefore, functionally, this necessitates a "leap" from one air/fuel ratio to another if maximum oxygen utilization is desired. This leap is problematic but achievable, especially when a variable valve train is fitted to the engine, as was the case with BMW's Hydrogen 7 engine. Kiesgen et al. (2006) described the control steps to ensure the switch is invisible to the driver. They also found that when operating at full load, the Hydrogen 7 engine reached $\lambda = 0.97$ (i.e., slightly rich) to provide excess hydrogen to reduce the NOx in the catalytic converter because hydrogen is a strong reducing agent. However, this does mean that some unburned hydrogen would escape into the exhaust system, leading to an efficiency penalty.

Kawamura et al. (2009, 2010) took a different approach to the EAT system. Instead of employing a TWC, they used a combination of a NOx storage reduction (NSR) catalyst in tandem with a diesel oxidation catalyst (DOC). This approach also used hydrogen as the reductant, but at a slightly lower fuel consumption penalty than Kiesgen et al.'s (2006) approach. Kawamura et al. (2009, 2010) reported a NOx reduction rate of 98% for an increase in hydrogen consumption of only 0.2%–0.5%. Although ammonia is usually used as a reductant in a selective catalytic reduction (SCR) system, hydrogen is a much stronger reagent in this respect. Hence, using the technology has less impact at the system level for a hydrogen vehicle than, for example, for a conventional diesel one. Nonetheless, reducing the fuel consumption penalty associated with employing it is clearly important. Naganuma et al. (2010) discussed how an NSR catalyst can be controlled by an occasional rich fueling spike within the engine. In counterpoint, Kufferath et al. (2021) recently proposed using an SCR system to control NOx, but with conventional urea used to reduce NOx. They argued that as SCR technology is now mature for diesel engines, the NOx loading rate would be lower for a hydrogen engine. Thus, further work is necessary to prove that using hydrogen as a reductant is as robust as using the now widely available "AdBlue" fluid.

Another means of controlling engine-out NOx emissions is to use EGR. Functionally, this is possible for the same reason that hydrogen engines can be operated at very lean air/fuel ratios: the very high LBV of the fuel means such engines will tolerate extreme dilution. Unlike the use of EGR in conventional SI engines, however, the operating strategy is more like that in diesel engines. This is because in a stoichiometrically operated SI engine, EGR is used as an inert diluent to maintain operation at $\lambda = 1$ to allow a TWC to function. Operation at $\lambda = 1$ is not always necessary for a hydrogen-burning engine because NOx emissions can be very low anyway. Thus, in a hydrogen engine with EGR, oxygen makes up a significant proportion of the gas being recirculated from the exhaust to the intake. Nevertheless, with EGR, operation much closer to $\lambda = 1$ is possible than with just air. Naganuma et al. (2010) showed that using EGR operation at $\lambda = 1.2$ is possible with significantly lower NOx emissions (up to 91%) than operation without EGR at $\lambda \leq 2.0$ in some areas of the operating map. In their work, while BTE reduced, this efficiency drop was presumably to some degree a result of the increased pumping work through the EGR loop. Importantly, they also investigated using an NSR catalyst and a DOC, the combination of which was capable of a further 92% reduction of NOx emissions.

Finally, one can use water injection to control NOx. Again, this water is a form of diluent. However, while there is a reduction in flame speed associated with the presence of water molecules in the combustion chamber, there is also a benefit in terms of base temperature reduction due to the latent heat of the liquid water. Hence, there are functional differences depending on how the water is introduced (i.e., indirectly via the intake ports or directly via a dedicated in-cylinder higher pressure injector). The latter is clearly more expensive to implement but ensures that the water vaporization effect occurs exactly where it is most beneficial. Water injection is arguably easier to implement for a vehicle fitted with a hydrogen engine, where there are no carbonaceous emissions that could lead to undesirable effects in the water harvesting, storage, and introduction systems. Böhm et al. (2016) discussed these issues for the application of the technology for a gasoline DI engine. They showed that the formulation of gasoline affects the condensate properties significantly. They added that acidity levels as high as pH 3 are possible for high-alcohol-content fuels (they stated that pH 5 is the minimum acceptable value). Straight condensation from the exhaust would seem more feasible for hydrogen engines. Clearly, the amount of water that can be injected is limited to less than that which can be harvested if an extra tank that has to be topped up by the operator is to be avoided.

Finally, the subject of catalyst protection must be addressed. As stated earlier, hydrogen combustion is very hot, with the heat flux to the catalyst concomitantly high, especially with operation at stoichiometric conditions. With gaseous fuels, the typical SI approach of fuel enrichment to limit exhaust temperatures will not work because such strategies primarily depend on the heat capacity of the unburnt fuel. Generally, slightly lean operation, with the unburnt oxygen absorbing some of the heat, can be used. However, this would put the engine into a high-NOx producing region, which a TWC would then not be able to process. BMW reported a strategy of switching a cylinder within a bank to the low-NOx range. Then, the resulting excess oxygen is available in the exhaust gas to bulk cool it before it strikes the catalyst. They reported that another cylinder (out of the six) could be switched, if necessary. Any power loss was considered to be equal to that potentially needed in extreme catalyst protection measures in a gasoline SI engine (Kiesgen et al. 2006). Although the BMW engine was naturally aspirated, it is assumed that such approaches would also be acceptable for turbocharged ones (in which the turbine is typically in front of the catalyst in the exhaust gas run). Future research on this should be conducted.

In summary, hydrogen combustion in engines presents many opportunities for reducing emissions. Those of hydrocarbons, CO, and CO_2 are eliminated (assuming lubricant consumption can be controlled), while particulate matter from fuel combustion is non-existent. Further, NOx, which easily forms since hydrogen combustion is very hot, can be controlled using the ultra-lean potential of hydrogen operation and relatively simple post-treatment systems. The latter can take advantage of hydrogen being an extremely strong NOx reductant, meaning a second fluid need not be carried for an SCR system. Further, the fuel consumption penalty is relatively low. Research in this area must aim to fully optimize such systems as well as determine component protection strategies. Nonetheless, emissions from hydrogen combustion systems seem to be entirely controllable.

Opportunities for applying hydrogen as a fuel for non-automotive engines

Generally, non-LD transportation applications must carry significant amounts of energy and often have a relatively controlled ecosystem in which they operate. The former makes the penalty of the non-linear mass/displacement trade-off of the tank system less of an issue as well as the fast recharge of hydrogen tanks significantly advantageous compared with batteries. Such a fast recharge can also limit the infrastructure challenge. Further, engines become more efficient with size. Hence, HD non-automotive applications of hydrogen engines have significant potential. Many universities and engine consultancies are announcing new projects related to hydrogen ICEs, with an emphasis on such HD applications.

HD off-road

On-road HD diesel engines, which typically have capacities of over 2.0 liters per cylinder, are targeting a BTE of 60%. Provided such levels can be achieved with hydrogen combustion, SI combustion in larger engines could then play a role. However, mixing-controlled diffusion burning combustion systems should be developed. While many of the characteristics of the fuel could be useful here, the challenge regarding NOx formation will still have to be surmounted. Some of the expected improvements will be hampered by the increase in fuel consumption associated with operating the EAT system. However, this is already accepted in many such applications with the complications of diesel SCR systems. Operating costs may also be affected due to the need to replenish AdBlue fluid in the emissions control system. Hydrogen operation could therefore be seen as a potential simplification.

Some applications for eliminating particulate matter emissions (e.g., in subterranean mining applications and warehouses) may be opened up by hydrogen engines. Until now, it has been assumed that such applications can only be serviced by FCs. As the size of machines increases, so does the efficiency of the larger engines necessary to power them. The ability to use mechanical transmissions with optimal hybridization may thus prove overwhelming compared with PEM

FCs. Research into the crossover point at which this occurs would be beneficial. However, assuming that parity can be reached, the engine would initially be expected to have a lower powertrain cost as well as reduced maintenance costs.

Railroad and maritime

Many of the points above apply equally to railroad and marine transport. As engines increase in size, the efficiency increase will become more important, as will the reliability associated with them. This advantage cannot be understated, especially in maritime applications, where replacing the propulsion system due to failures in the field is not viable for larger crafts. Although FCs could be made modular for swap-out purposes, the primary issue is that PEM devices are simply not efficient enough. The SOFC–GT hybrid system could be a longer-term potential prime mover for shipping. The efficiencies of this system are not only routinely predicted to be above those of large engines, but there is also the potential to have a mechanical power output for at least part of what is produced. However, until this technology matures, there is no real competitor to the ICE for marine use. Further, in addition to mitigating CO_2 emissions, it must be made considerably cleaner for emissions control areas. While hydrogen has advantages in combustion, ammonia is arguably a better energy carrier for marine applications. (Methanol may be ideal for marine use in that it is liquid, fully miscible with water, non-toxic to marine life, and can be stored easily aboard a vessel. However, the carbon used to make it would have to be sourced from the biosphere.)

Using waste heat recovery, ammonia could be converted into a mixture of hydrogen and nitrogen for use in an engine's combustion system, which could improve combustion. However, the complete conversion of two moles of (liquid) ammonia to three (gaseous) moles of hydrogen and one of nitrogen essentially makes this a hydrogen combustion system with extra nitrogen present. Hence, NOx emissions would need to be monitored closely. However, as discussed in the subsection titled "Engine performance and operating strategies with DI (internal mixture preparation)," ammonia or hydrogen could be used in an SCR post-treatment system to mitigate these emissions. Therefore, no extra fluids would have to be carried to achieve compliance in this regard.

The railroad application of the PEM FC is also being driven by emissions. For instance, Californian railroad emissions standards are being tightened considerably and are expected to reach Federal Tier 5 in 2025, severely limiting hydrocarbons, particulate matter, and NOx emissions (Hoffrichter 2019). Some of the technologies discussed above should allow adherence to all these limits using a combustion engine. Efficiency will then become the main issue. Since rail traction is generally performed using electric transmission, the FC now has an advantage over the ICE in this application for two reasons. The first reason is that it does not require a generator. Second, the associated losses are lower. Nevertheless, since locomotives generally operate at high power loadings, the efficiencies at those points do not make a compelling case for FCs (Kurtz et al. 2017). An opportunity for HD hydrogen ICEs might arise if the requirement to drive a generator can be offset by high engine efficiency such that the overall system efficiency is superior.

Aviation

While hydrogen has been used in rocketry, its use in conventional aviation is more restricted. Air-breathing hydrogen engines, however, are uncommon in aviation because small engines are not efficient enough for light aviation use. This is important because of the impact on how much hydrogen must be carried and the consequent mass of the storage system. Conversely, because they are more efficient at cruise speeds, PEM FC light aircrafts are being developed for short-range operation and applications where power must be modulated relatively quickly.

In larger applications, considering a long range, the SOFC–GT hybrid powertrain system is being studied for aviation use (also incorporating high-power battery usage), and these configurations promise very high efficiencies (Collins and McLarty 2020). Regarding fuel for combustion in aviation GTs, Pratt and Whitney successfully converted existing turbojet engines such that hydrogen can be used, as well as developed the Project 304 "Suntan" engine. This engine used a novel cycle in which liquid hydrogen was pressurized to 200 bar and then heated and expanded through a turbine to drive the engine's compressor (Mulready 2001). The remainder of the hydrogen not used for heating the heat exchanger was then burned in an afterburner. For more details, see Mulready (2001) on the Rae expander cycle and its novel approach to using the physical energy invested into hydrogen to make it storable.

Hydrogen is of interest in such aviation applications for a variety of reasons. When stored cryogenically, the very low temperature can be used to supercool motors and electronics to reduce conduction losses. As such, it offers a number of other benefits beyond being a zero-carbon energy carrier. Indeed, aircraft manufacturers such as Airbus are investigating how using liquid hydrogen as a fuel will allow or require changes in aircraft architecture, with real impetus behind its adoption in this domain (Airbus 2021).

Future potential of hydrogen in non-conventional engines

The Wankel engine

The potential synergies between hydrogen combustion and the Wankel engine have long been discussed (Salanki and Wallace 1996). The unidirectional nature of the rotor motion of the Wankel engine means that the four phases of the Otto cycle are spatially separated from each other (Yamamoto 1981). Being able to delay introducing hydrogen into the air until after the exhaust port has shut, thus eliminating backfire, is a potential advantage. Some hydrogen Wankel engines have employed a form of DI where the gas is introduced near the major axis. This approach takes advantage of the long intake phase (50% longer than that in a reciprocating four-stroke engine) and the fact that the injector is then shielded from maximum chamber pressure during combustion (Mazda 2021). Furthermore, the generally increased volumetric efficiency of the Wankel engine can compensate for the oxygen displacement effect of hydrogen owing to the porting arrangement and lack of valves. This also ensures that no hot exhaust valves exist in the combustion chamber to initiate PI and backfire. Instead of using one-piece injectors, dedicated hydrogen injection ports have been deployed (Salanki and Wallace 1996). Alternatively, Mazda's original HRX hydrogen rotary engine included a dedicated hydrogen intake port timed by a camshaft (Cranswick 2016). Hence, newly developed injection equipment offers advantages over the relative mechanical complication (compared with the simple Wankel engine) of using a dedicated extra mechanism.

The high LBV of hydrogen can overcome one of the problems of the Wankel engine, as it takes a very long time for the flame to traverse the long combustion chamber. This situation is compounded by the fact that the rotor is moving away from the advancing flame front. Using hydrogen leads to more rapid combustion and can also burn the mixture in the trailing part of the chamber more rapidly. The basic engine does, however, suffer from a very poor SVR. This combined with the short quenching distance of hydrogen means that the heat losses are likely to be significant, although this may actually help make the Wankel engine more tolerant to hydrogen. Salanki and Wallace (1996) cited Swain, Swain, and Adt (1988) in this respect.

The disposition of the operating phases around the periphery of the trochoidal housing can also permit more targeted cooling arrangements. In theory, the Wankel engine can readily adopt thermal barrier coatings, which could also help offset the heat loss issue (Kamo, Kakwani, and Hady 1986). These are all potential avenues for future research, as is perhaps the resurrection of the John Deere/NASA Direct Injection Stratified Charge (DISC) combustion system. Under this system, a pilot jet is ignited by a spark; this pilot then causes the main jet to ignite, combusting the fuel in a diffusion-burning manner. This would appear to be eminently suited to hydrogen combustion. Moreover, given that jets can be kept away from the walls, it might promise significantly improved efficiency. Modern computational fluid dynamics approaches could offer potential to assist in the optimization here.

In light of the above potentialities, after initiating a hydrogen rotary engine research program with the HRX, Mazda offered a Wankel-engined hydrogen RX-8 for lease in 2006. Instead of the eccentric shaft-driven camshaft used to time the introduction of low-pressure hydrogen into the working chambers, it combined DI and PFI (Mazda 2021). Mazda's offering just predated the BMW Hydrogen 7. A Premacy model with a series hybrid drivetrain powered by a version of this engine was also developed later. This suggests that the Wankel engine may be more easily converted to a hydrogen combustion engine than a reciprocating engine for all the reasons discussed in relation to both types. With further research, this could become an important option in the future, despite the current inefficiency of conventional gasoline versions. Nevertheless, significant potential exists for the Wankel engine, especially perhaps as a range extender engine for an electric vehicle. Another option would be a mixing-controlled combustion system such as the John Deere/NASA DI stratified charge arrangement, a more efficient device. In either case, further investigation is desirable.

The two-stroke engine

Synergies between the two-stroke cycle and hydrogen combustion

The two-stroke cycle is arguably better suited to road transport than the four-stroke, certainly when SI combustion is considered. This is because load control by throttling in the four-stroke increases pumping work considerably. By comparison, as the two-stroke lacks dedicated intake and exhaust strokes, it does not suffer from these losses. The disadvantage is that because of its poorer trapping efficiency, it is normal for two-stroke engines to lose charge down the exhaust. This increases both fuel consumption and emissions markedly in premixed charge engines.

DI can be used to offset these shortcomings by delaying the fuel introduction until after the ports close. However, a TWC cannot be used to convert NOx because some fresh air is inevitably lost, causing the catalyst feed gases to become lean overall. The two-stroke requires half the load from its complete cycle to match the torque of an equivalently sized four-stroke. This is a major advantage because the in-cylinder pressures and temperatures required to achieve the same flywheel output are lower, reducing NOx directly. Upon accepting that overall lean operation is an unavoidable factor and that hydrogen combustion is greatly simplified if it is constrained to lean conditions, a synergistic relationship between the engine and fuel appears. However, the reasons for this differ between the Wankel and hydrogen. While operating at $\lambda \geq 2$ in the cylinder necessarily reduces the output in each cycle, the twice as high firing frequency can mitigate this impact. Further, the same approach to NOx at higher loads can be used as that proposed by Kawamura et al. (2010), namely, adopting an NSR catalyst and a DOC. The fact that hydrogen combustion does not produce any emissions arising from the combustion of carbon (of course oil control must be robust) means that the emissions penalty of the two-stroke operating on conventional hydrocarbon fuels is eliminated by using hydrogen. Hence, the engine type and fuel appear to be peculiarly well suited, and further research is warranted. While heat rejection could remain an issue, a specific type of two-stroke engine could improve this significantly, as discussed next.

The opposed-piston two-stroke engine

This type of engine has exceptionally good thermodynamic properties, especially due to its very good SVR at top dead center (Wilson 1946; Pirault and Flint 2010). Further, with uniflow scavenging, the opposed-piston two-stroke engine can be expected to yield benefits in terms of trapping and exhaust lambda control (Turner et al. 2019). Its architectural problem, namely, that fuel and ignition have to be located on the circumference of the cylinder bore, is offset by the high diffusivity of hydrogen allowing it to mix more readily after introduction with its high burning velocity offsetting the position of the ignition source. Recall that Younkins, Boyer, and Wooldridge (2013) achieved higher thermal efficiencies using two spark plugs at the periphery of their engine's combustion chamber, while the injector was in the center. Mixing-controlled diffusion burning may also be simpler to achieve with the opposed-piston two-stroke scheme for two main reasons. The first is because of the high swirl maintained in the combustion chamber, and second, there is greater opportunity to direct fuel plumes across the chords of the cylinder within that swirling air flow. Further, since opposed-piston two-stroke engines typically have a larger swept volume, such a hydrogen-burning version could have potential for HD applications, from trucks to marine and stationary applications.

The free-piston engine

Besides all the advantages of combining the two-stroke cycle with hydrogen, free-piston engines (FPEs) generally use the cycle, meaning such a combination could form an excellent in-vehicle range extender. An FPE does not contain a cranktrain as such. The crankshaft and connecting rod are instead replaced by a "mover" that converts the expansion energy to work, with modern embodiments generally taking this work as electricity produced by a linear generator. Mechanical efficiency improves by removing side thrust and bearing friction, and there is an opportunity to vary top and bottom dead center positions, and with it, the CR. Van Blarigan and coworkers at Sandia National Laboratory proposed such a combination and conducted experiments to reinforce the adoption of hydrogen in a homogeneous charge compression ignition combustion system (Van Blarigan, Paradiso, and Goldsborough 1998; Goldsborough and Van Blarigan 1999). This system tends to result in highly reduced NOx emissions regardless of the fuel. Additionally, with the FPE's ability to vary its CR to control this, this could control NOx emissions within the combustion process. Indeed, a variable CR can allow sparkless combustion with a wide variety of fuels in two-stroke engines with conventional cranktrains. This is expected to be portable to FPEs in a similar manner to that reported by Sandia researchers (Blundell et al. 2010; Turner et al. 2010).

Overall, investigating hydrogen in two-stroke engine systems is highly desirable, especially if an opposed piston form could be made to work.

The SOFC–GT engine

In larger HD applications, the cyclic combustion engine should be capable of being developed to provide better in-vehicle fuel economy than a PEM FC. However, the same is not true in relation to the SOFC, particularly when it is compounded by a GT to create a SOFC–GT hybrid system. The SOFC operates at far higher temperatures than the PEM, which leads to operational challenges (i.e., very long start-up times). However, compounding it with a Brayton GT cycle (which can be either topping or bottoming) is logical. The higher operating temperature also means that the catalyst loading required for the electrochemical reaction does not have to be as high as it is in the PEM device, thus potentially providing some cost benefits.

Such SOFC–GT hybrid systems have been predicted to have extremely high thermal efficiencies (in terms of fuel energy into electrical power), with 65%–70% forecasted for larger applications (Cunnel, Pangalis, and Martinez-Botas 2002; Azizi and Brouwer 2018). These systems are being studied for a variety of larger applications, even with regard to aviation (Collins and McLarty 2020). In aviation, if liquid hydrogen is used, as mentioned above, there is an opportunity to use it to supercool electronics and motors and thus increase the efficiency of those components as well. Alternatively, when combined with a further steam bottoming cycle, overall efficiencies as high as 80% have been predicted (Azizi and Brouwer 2018).

This remarkable potential is a result of 80%–85% of the energy being converted electrochemically in the SOFC, a proportion therefore not limited in efficiency by the Carnot cycle. However, because SOFC–GT hybrid systems are high-temperature devices, a significant amount of high-temperature waste heat can be harvested by the compounding GT device. While the proportion of heat rejected is similar in the PEM and SOFC, it is very low grade in the PEM and essentially useless. The GT in a SOFC–GT plant instead produces 15%–20% of its total power. However, while the efficiency of this device is more limited, its contribution makes up a relatively small proportion of the overall contribution. Furthermore, the work from the turbine can be applied mechanically, which may raise in-vehicle efficiency if it can be used in such a manner.

When using hydrogen as the fuel, we can also envision an SOFC–GT hybrid power plant as part of an integrated power generation scheme in which renewable energy is used to electrolyze water. Moreover, the resulting hydrogen can be stored for later recombination in the power plant. The very high efficiency of the plant helps make this approach more practical. Hence, owing to its extremely high-efficiency potential, a SOFC–GT operating on hydrogen is worthy of further study.

Research gaps and opportunities

The foregoing discussion shows the vast potential for studying the use of hydrogen in combustion engines. However, some aspects require further research and development, primarily the fuel injection equipment. This must be of the DI type, since backfire and PI severely limit the potential in four-stroke engines and such DI equipment would be necessary for two-stroke engines anyway. Further, higher pressure equipment may be needed for mixing-controlled diffusion burning. The means of achieving this process should be researched because of the chance of increasing efficiency by reducing heat rejection and eliminating knock. However, this may require the development of high-pressure hydrogen pumps for some applications.

The two-stroke cycle engine merits study in conjunction with hydrogen since it promises greater efficiency and because of its synergy with hydrogen's combustion characteristics. The opposed-piston type would appear particularly well suited in many respects because of its beneficial heat rejection characteristics.

Post-treatment systems and control must also be analyzed further based on the operating strategy. In four-strokes employing a "lambda leap," the strategy will differ from that in engines that only ever operate lean to limit NOx emissions. In parallel, strategies to provide thermal protection for components in the exhaust stream need further investigation.

The opportunity to employ the Miller cycle (with a high expansion ratio) to limit knock would be worth researching. Another potential research direction would be to examine the use of water injection and associated water harvesting from the exhaust, especially whether the gathered water has a useful pH value. The issue of hydrogen building up in the crankcase also needs attention, as does whether it can be catalyzed on its way through the breather system. Moreover, with respect to very high energy conversion efficiencies in larger plants, the SOFC–GT hybrid system operating on hydrogen should be investigated further.

Finally, for larger applications that merit it, recovering some of the energy from storing hydrogen must be researched. Liquefying hydrogen or pressurizing it to 350 or 700 bar requires a significant energy input. As hydrogen's constant pressure is approximately 10 times that of air, a means to generate power from the process of feeding it from a tank to an engine system could improve overall vehicle system efficiency. This is at the root of the Rae expander cycle used in the Suntan engine, where the hydrogen turbine was considerably smaller than the air compressor to which it was attached. While energy systems use only the heating value of the fuel and overlook the associated physical energy, this can raise system efficiency at the expense of the hydrogen supplier.

Conclusion

This chapter reviewed many aspects of hydrogen as a fuel and its interaction with engines, specifically for HD applications. It was shown that with its use in combustion engines, in-vehicle efficiencies should be higher than those of a PEM FC. DI fuel systems will be a necessary technology to achieve this, with many further avenues to pursue once they are productionized. While post-treatment arrangements are understood, detailed work is needed to minimize the fuel consumption penalty associated with their operation. How best to apply any necessary component protection strategies to prevent them from being damaged by excessively high temperatures also demands future research.

There are interesting possibilities to improve in-vehicle efficiencies further as a result of the synergies between hydrogen combustion and alternative engine types. Among cyclic combustion types, the Wankel engine may have some potential, especially with mixing-controlled combustion systems. However, the two-stroke cycle could improve efficiency over its four-stroke equivalent, especially in the form of the opposed-piston architecture. Further improvements may also arise from using an FPE arrangement. This would have to be very high efficiency because it only generates electrical power in its modern incarnation.

A form of alternative engine that promises to significantly beat both the PEM FC and optimized HD engine is, almost ironically, another FC type. This is the SOFC–GT hybrid, for which extremely high efficiencies should be achievable. Operational challenges must be addressed due to the length of time it takes to heat up. Nonetheless, the potential efficiencies (around 65%–70% or higher) make attempting to address these worthwhile. The duty cycle of large ships would seem immediately suited to them, but they may also become practical for aviation. Stationary power generation as part of base load, perhaps employing hydrogen electrolyzed during the day using renewable power, also appears to be a significant opportunity.

Finally, we discussed the perceived research and technology gaps. This work shows the significant potential of hydrogen combustion engines, which could form an important part of the future technology mix for carbon-free transportation.

Abbreviations

BEV	Battery electric vehicle
BTE	Brake thermal efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression ratio
DOC	Diesel oxidation catalyst
DOE	Department of Energy
DI	Direct injection
EAT	Exhaust after treatment
EGR	Exhaust gas recirculation
FC	Fuel cell
FPE	Free-piston engine
GT	Gas turbine
HD	Heavy-duty
ICE	Internal combustion engine
LBV	Laminar burning velocity
LD	Light-duty
NOx	Nitrogen oxide
NSR	NOx storage reduction
PEM	Proton exchange membrane

PFI	Port-fuel injection
PI	Preignition
SCR	Selective catalytic reduction
SI	Spark ignition
SOFC	Solid oxide fuel cell
SOFC–GT	Solid oxide fuel cell–gas turbine
SVR	Surface area-to-volume ratio
TWC	Three-way catalyst
λ	Relative air/fuel ratio
ϕ	Equivalence ratio

Note

1 Low-temperature FC efficiencies are often quoted using the lower heating value of the fuel. However, this is not always the correct approach, since the exhaust temperature of a PEM cell is generally lower than the dew point of water. Therefore, the higher heating value should be used. For hydrogen, the ratio of the higher heating value to the lower heating value is the highest among that of all fuels, at 1.175, and this would cause a significant drop in quotable efficiency. While of little practical difference when the cost of operating a vehicle is considered, this remains a valid scientific point.

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KACST'S R&D ACTIVITIES TOWARD A CLEAN HYDROGEN ECONOMY

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Introduction

Moving to zero- or low-carbon emission technologies to mitigate carbon dioxide (CO_2) emissions has received growing interest. Many countries, including Saudi Arabia, have committed to meeting the Paris Agreement to combat climate change. Indeed, the decarbonization of global energy systems is a major factor in achieving a sustainable energy economy during the transition to clean energy systems.

Reaching many countries' ambitious climate commitments to reduce global CO_2 emissions and achieve carbon neutrality requires many actions. These actions include the expansion of renewable energy source deployment and use of low-carbon fuels such as hydrogen and biofuels. Hydrogen can play a significant role in achieving a decarbonized global energy system. Owing to its versatility as an energy carrier, it has emerged as a potential energy source for power generation, transportation, and manufacturing applications (Rosen and Koohi-Fayegh 2016). When hydrogen is utilized directly in these sectors, zero-carbon emissions are attainable.

Most global hydrogen production is dominated by fossil fuel-based processes. Gray hydrogen is commonly used to distinguish this type of production. Steam methane reforming (SMR) and coal gasification are the two most common methods for producing hydrogen. However, if these hydrogen production methods are equipped with CO_2 capture and storage, the hydrogen type is classified as blue. It is not necessary to utilize the captured CO_2 to qualify as blue hydrogen. When renewable electricity is utilized to produce hydrogen from water, the hydrogen type is identified as green. Green hydrogen refers to the production of hydrogen without CO_2 emissions. Another type of hydrogen that is not as common as gray, blue, and green hydrogen is turquoise, which is located between the blue and green types.

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Turquoise hydrogen is produced by fossil fuel pyrolysis at high temperatures in the absence of oxygen. The carbon content of fossil fuels is converted into solid black carbon during this process, which can be used in different industrial applications.

King Abdulaziz City for Science and Technology (KACST) has already contributed to Saudi Arabia's sustainable energy vision by helping develop decarbonized local energy systems to meet its climate commitments. KACST, established in 1977, is a national agency for research and development (R&D) in science and technology that aims to foster the country's development. It has also developed mechanisms to transform the outputs of scientific research and technical development into industrial products. A primary responsibility of KACST is to coordinate with relevant authorities in the Kingdom to develop strategies and plans to help enhance economic growth.

KACST has been active in the hydrogen industry since the 1980s. In February 1986, the Federal Republic of Germany and Kingdom of Saudi Arabia (represented by KACST) signed a bilateral agreement for a program of research, development, and demonstration of solar hydrogen production. One major R&D project was HYSOLAR, which was conducted between 1986 and 1995. The HYSOLAR project aimed to produce hydrogen from solar energy through electrolysis (i.e., splitting water to obtain hydrogen from water molecules). First, a 2 kW electrolyzer was built for research purposes, followed by the construction of a 10 kW electrolyzer. After two years of design, 350 kW electrolyzer was implemented in the solar village in Aluayyna in 1993. This 350 kW electrolyzer has been described as the "first-time achievement of a solar hydrogen system on industrial demonstration scale" (Winter and Fuchs 1991, 723–34) and "the world's first technical prototype of a pressurized electrolyzer fueled by intermittent solar" (Schucan 1999, 165–6).

KACST has since revisited hydrogen technologies by examining the entire hydrogen value/supply chain (i.e., production, distribution, storage, and utilization). R&D activities have focused on proton exchange membrane (PEM) fuel cells. In addition, materials have been developed to reduce the cost of hydrogen ($/kg) and for effective storage of hydrogen gas for electrolyzers. In October 2022, a dedicated center for developing hydrogen-related technologies, called the National Center for Hydrogen Technologies, was established at KACST.

KACST, in collaboration with various research, development, and innovation ecosystem stakeholders, has recently proposed a long-term strategy to support the national hydrogen plan of the Kingdom. This plan aims to include hydrogen in the national energy economy and become a world leader in the low-carbon hydrogen market. The proposed strategy is important for overcoming challenges and exploiting opportunities throughout the clean hydrogen production and utilization value chain. The strategy is composed of three main programs. First, research support programs to promote and encourage research on hydrogen production and storage technologies in national universities and research institutions. Second, prototyping and testing programs for proof-of-concept solutions aiming to improve hydrogen production and storage in the Kingdom. Third, commercialization programs to help

R&D research outputs reach markets. Therefore, one of KACST's primary activities is to explore and develop clean and novel hydrogen production technologies.

In summary, KACST, as a research leader in Saudi Arabia, is participating primarily in the R&D segment in the hydrogen energy value chain. to address several challenges associated with hydrogen production. Hydrogen deployment in the global energy economy is expected to increase significantly in the future. Therefore, KACST is working with a broad range of local and international institutions and industries to play a central role in advancing the Kingdom's hydrogen economy. Given that Saudi Arabia has cost-effective access to natural resources, KACST is planning to expand its role in the hydrogen industry by researching a variety of zero- and low-carbon hydrogen types. In addition, Saudi Arabia's cost of renewable electricity is low, which greatly affects the hydrogen delivery cost. Therefore, some of KACST's R&D activities have focused on the development of practical, environmentally friendly, and cost-effective technologies for hydrogen production and utilization.

Research activities

This section describes the ongoing low-carbon hydrogen-related R&D activities at KACST to support the Kingdom's national hydrogen strategy so as to accelerate the deployment of clean hydrogen in local and global energy systems.

Hydrogen production using advanced microwave systems

Owing to the economic advantages of hydrocarbon reforming for large-scale hydrogen production, global production is expected to continue to be dominated by fossil fuel sources in the near future (Turner 2004). The most common method to produce hydrogen is through the thermal process of steam reforming using natural gas as a feedstock (Kalamaras and Efstathiou 2013). The main issue with this method is the significant amount of CO_2 generated during the process (Ogden 2002).

KACST, through its KACST–Oxford Petrochemical Research Center, has been working on potential alternative ways to produce CO_2-free hydrogen and solid carbon from fossil fuels by combining microwave energy and heterogeneous catalysts (TRL 3), as Figure 24.1 illustrates. Its study found that high volumes of high-purity hydrogen can be rapidly produced using inexpensive fine iron particle catalysts through microwave-initiated reactions. Further, the catalytic dehydrogenation of fossil fuels such as extra-heavy crude oil, crude oil, diesel, petrol, and methane can be achieved upon the microwave irradiation of the samples. A considerable volume of high-purity hydrogen, over 90% of the volume in the exiting gas stream, follows this dehydrogenation process (Jie et al. 2019).

The microwave heating of heterogeneous catalysts is different from thermal heating in two fundamental ways (Horikoshi and Serpone 2014, Horikoshi et al.

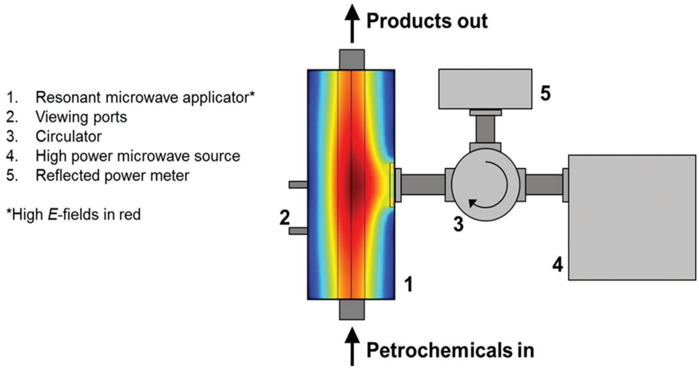


FIGURE 24.1 The microwave system design in flow mode. The feedstock flows along the axis of the applicator at the antinode of the TM010 mode. In this region, there is the minimal depolarization of the sample and maximum coupling to the electric field.

Source: Aldawsari (2017).

2011). First, as opposed to thermal heating, where heat is transferred to the sample through the system boundaries, microwave heating is selectively generated throughout the sample in areas of high microwave absorption. Based on the distribution of microwave absorbers within heterogeneous mixtures, the fields can cause the formation of hotspots (Horikoshi and Serpone 2014, Horikoshi et al. 2011). These hotspots are driven by very high electric fields and can lead, among several effects, to highly localized superheating at their surface. This phenomenon occurs at the interface between the metal catalyst and reactants, inducing significant temperature gradients between the catalyst particle hotspot and surrounding atmosphere. In this study, the resulting non-equilibrium localized superheating applied to the metal particles is thought to accelerate the release of hydrogen through the catalytic decomposition of alkanes in a deep dehydrogenation reaction as well as C-H bond cleavage over the C-C bond (Edwards et al. 2016, Gonzalez-Cortes et al. 2016). Second, the high electric fields associated with the polarization of the metallic particles will also significantly increase the microwave dielectric heating of the particle surface; thus, any plasma generation and field ionization will facilitate dehydrogenation processes (Edwards et al. 2016, Gonzalez-Cortes et al. 2016).

In terms of the energy balance, microwaves are considered to be a complex system, especially when combined with heterogeneous catalysis. Therefore, it is challenging to determine their efficiency precisely. In particular, the previously reported microwave single-mode bench-scale system is a simple system that does not consist of impedance matching.

The initial evaluation considered the thermodynamic analysis of the process of decarbonizing diesel as a model compound of crude oil. It found that the minimum amount of energy needed to complete dehydrogenation is theoretically approximately 1.4 MJ per kg of diesel. In addition, the produced hydrogen has an enthalpy of combustion of 18.25 MJ per kg of diesel, which indicates a positive value for the net energy balance (NEB):

$$\text{NEB} = \frac{\text{Enthalpy of combustion of produced hydrogen}}{\text{Electricity consumption}}$$

Generally, several aspects can affect the NEB, such as the amount of absorbed microwave power, which can be influenced by the whole catalytic system. Therefore, the entire microwave system requires further optimization and integration to raise efficiency and become closer to the theoretical values (Jie et al. 2019). Moreover, the catalytic dehydrogenation of various hydrocarbon sources leads to the production of pure solid carbon as a by-product. The resulting carbonaceous materials are carbon nanotubes, which may have high values (Gonzalez-Cortes et al. 2016). Figure 24.2 illustrates a scenario for hydrocarbon dehydrogenation using microwave dielectric heating for the hydrogen fuel economy.

Overall, the abovementioned research describes a novel advancement in the microwave-activated catalytic process for the rapid release of hydrogen using safe and abundant storage materials. Considerable engineering work is required to transfer this discovery from the laboratory to large-scale application. However, the storage and rapid release of hydrogen from hydrocarbons, oils, and plastic waste could initiate an attractive and new path toward a decarbonized hydrogen economy. High levels of hydrogen production can be improved or maximized by evaluating alternative bimetallic catalytic system nanoparticles. This would enable the magnetic recovery of the catalysts or their potential use for scale-up processes and/or varying the microwave parameters and optimizing the reaction.

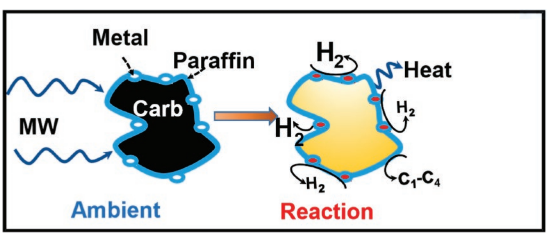


FIGURE 24.2 Catalytic decomposition of paraffin wax over a carbon/metal catalyst under microwaves.

Source: Gonzalez-Cortes et al. (2016).

Development of heterogeneous catalysts for using electrolysis to produce green hydrogen

Water electrolysis is an efficient technology for producing hydrogen with no greenhouse gas emissions. Electrolysis accounts for approximately 4% of the world's hydrogen demand and has recently been promoted as the preferred path for decarbonized energy systems (Royal Society 2018). Electrolysis is a more energy-demanding technology than other hydrogen production methods, which limits its use. However, the dedication of renewable energy sources to this type of hydrogen production, especially in regions with low-cost renewable electricity such as Saudi Arabia, may make this technology an attractive option for large-scale applications. Another limitation to the widespread use of this technology is the use of electrocatalysts to enhance the electrochemical water splitting of the hydrogen evolution reaction to generate hydrogen. However, in the last five years, the global green hydrogen supply from electrolyzers has doubled (IRENA 2020).

The commonly used catalyst in electrolysis is platinum (Pt) because of its high catalytic activity. However, platinum is an expensive and rare metal, which limits its large-scale application. Therefore, a group of researchers at KACST has developed methods to produce efficient, stable, and low-cost nanocatalysts. Metal nanoparticles are clusters of tens to thousands of metal atoms, with sizes ranging from 1 to 100 nanometers (nm). They are appealing catalysts because of their large surface area and small size, which result in superior catalytic activity. Consequently, many studies have investigated metal nanoparticles loaded on various supports for heterogeneous catalyst applications in organic and inorganic reactions, industrial processes, and selective oxidation reactions.

For instance, Khdary and Ghanem (2014, 2016) developed metal nanoparticles incorporated into support matrix materials such as silica and titania using a variety of techniques such as wet impregnation, ion exchange, and chemical surface modifications. In their studies, metal precursors were attached to the support surface via pre-attached functional groups, followed by chemical reduction to form metal nanoparticles on the surface of silica or titania (Figure 24.3). The silica surface was chemically grafted with dithiocarbamate functional groups by treating it with a silane coupling agent, *N*-[3-(trimethoxysilyl) propyl] ethylenediamine, and CS_2. The Pt ions were then attached to the dithiocarbamate-modified silica, followed by chemical reduction to produce Pt nanoparticles with diameters ranging from 2 to 5 nm with a uniform shape and high dispersion, as shown by transmission electron microscopy (TEM). Electrochemical analysis showed that at an applied potential of more than −250 mV versus saturated calomel electrode the Pt nanoparticle-supported silica catalyst exhibited very high and stable electrocatalytic activity for hydrogen production with a mass activity of 11.9 A g Pt^{-1} mV^{-1}. The method is simple and allows for the easy and low-cost preparation of effective electrodes based on cheap silica substrates. Additional studies are underway to apply this method to the synthesis of other metals and bimetallic nanoparticles.

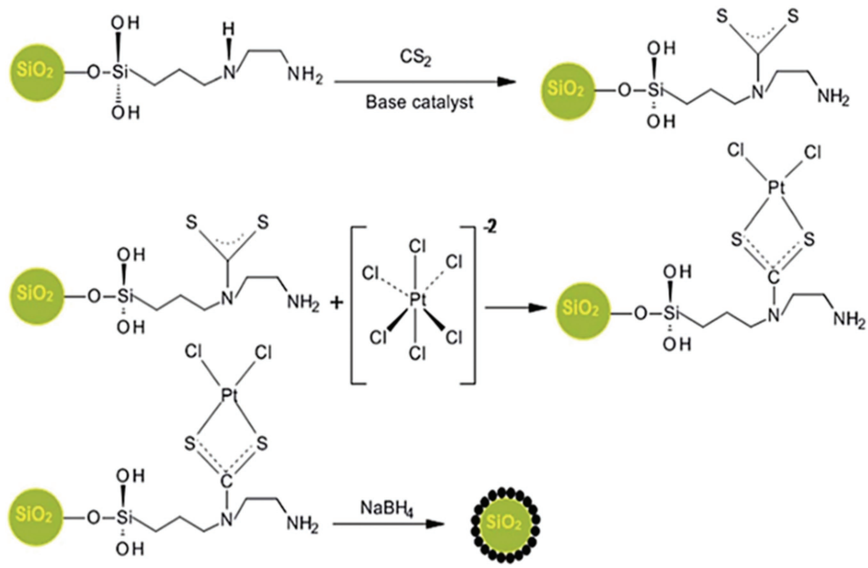


FIGURE 24.3 Modification of silica with dithiocarbamate, complexation with Pt ions, and reduction to Pt nanoparticles supported by the silica surface.

Source: Reproduced from Khdary and Ghanem (2014) with permission from the Royal Society of Chemistry.

In another study, a Pt/meso-TiO_2 catalyst was incorporated onto mesoporous TiO_2 (Ptx/meso-TiO_2) via the evaporation-induced self-assembly (EISA) of a surfactant template, followed by a two-step calcination process (Mabrook et al. 2020). The work demonstrates the successful preparation of the low loading of oxidized Pt nanoparticles (0.1–0.5 wt%) onto a mesoporous TiO_2 substrate using the EISA approach followed by a two-step calcination process. X-ray diffraction (XRD), Brunauer–Emmett–Teller, X-ray photoelectron spectroscopy (XPS), and TEM analyses confirmed the formation of highly dispersed oxidized Pt nanoparticles with an average diameter of 3 nm that were strongly bonded to the highly ordered mesoporous TiO_2 framework. Enhanced electrocatalytic performance was recorded for the Ptx/meso-TiO_2 electrocatalysts with a hydrogen evolution onset potential of −10 mV versus reversible hydrogen electrode (RHE), Tafel slope of −110 mV/dec, small charge transfer resistance, and mass activity up to 25.7 A/mg Pt at −300 mV versus RHE. It was suggested that such activity results from the strong bonding and accessibility of the oxidized Pt nanoparticles with the TiO_2 substrate. Furthermore, long-term stability under harsh acidic conditions is indicated by the Ptx/meso-TiO_2 catalysts, which are promising catalysts for the hydrogen evolution reaction in acidic solutions.

Khdary et al. (2019) developed a copper-based electrocatalyst film produced by the in situ electrochemical reduction of Cu(II). In their study, a Cu(II)-PEDA/

SiO_2 catalyst was synthesized using functionalized silica particles with *N*-(3-(trimethoxysilyl propyl) ethylenediamine as a linker. This was followed by treatment with a copper sulfate solution to form a Cu(II)-PEDA/silica complex. Thermogravimetric analysis and Fourier transform infrared spectroscopy analyses confirmed the surface modification of SiO_2 with PEDA. The catalyst was characterized by SEM, TEM, XRD, and XPS, which provided evidence of the formation and uniform distribution of Cu(0) nanoparticles on the surface of SiO_2. The loading of the Cu(0) was found to be 0.22 mmol g^{-1} using both the XPS and the EDS techniques. The Cu-PEDA/SiO_2 catalyst showed outstanding electrocatalytic activity for the hydrogen evolution reaction in a 0.5 M H_2SO_4 solution (Figure 24.4). The Cu-PEDA/SiO_2 catalyst had an overpotential η of −200 mV versus SHE and a Tafel slope of 67 mV dec^{-1}. Additionally, the catalyst exhibited good stability and consistently produced hydrogen at various potentials for more than two hours. This type of catalyst has the potential to reduce the cost of hydrogen production.

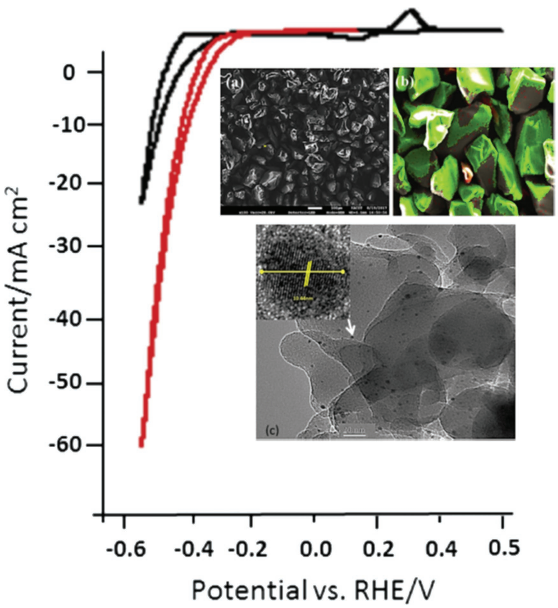


FIGURE 24.4 A scanning electron microscope (SEM) image of (a) plane silica before modification, (b) ultra-high resolution SEM (Gentle Beam Mode) with two detectors for the Cu(0)-PEDA/silica catalyst, and (c) TEM image of the Cu(0)-PEDA/Silica catalyst. The inset shows the TEM image of single copper particles.

Source: Reproduced from Khdary et al. (2019) with permission from Elsevier.

Development of solar-driven photoelectrochemical (PEC) water splitting for producing green hydrogen

The PEC splitting of water into oxygen and hydrogen using solar radiation is considered a promising solar-to-hydrogen electrolysis technology. To fulfill the sustainable energy objective, PEC systems must be cost-effective and stable in strongly alkaline or acidic electrolytes as well as harvest a large proportion of the solar spectrum. Despite the emerging high solar-to-hydrogen conversion efficiency of monolithic photovoltaic-biased PEC cells and multiple absorbers, the complexity of their fabrication and prohibitive cost hinder their use in large-scale applications. For metal oxides, large bandgaps[1] (usually larger than 2 eV) limit solar light absorption, which typically leads to lower solar-to-hydrogen conversion efficiency. Groups III–V semiconductors have been shown to have the highest efficiency for PEC water splitting. However, the prohibitive cost of single-crystalline wafers may limit their practical use and large-scale application.

Over the last 40 years, researchers have extensively investigated various semiconductors for water splitting (e.g., photoanodes and photocathodes). PEC water splitting uses semiconductor materials immersed in a water-based electrolyte. When incident sunlight strikes the surface of a semiconductor, photon energy is converted into electrochemical energy, which can split water into hydrogen and oxygen (see Figure 24.5). This process offers a long-term and cost-effective way to produce hydrogen without causing greenhouse gas emissions. However, the development of efficient semiconductor photoelectrodes with suitable bandgaps and band alignments remains challenging.

The concept of PEC water splitting was first demonstrated by Fujishima and Honda in 1972. A PEC cell consists of an anode and a cathode immersed in an electrolyte and connected to an external circuit under illuminated light. The design of efficient PEC water-splitting systems requires several key criteria. First, the photoelectrode must have a suitable bandgap to generate the water-splitting potential (>1.6 eV). Second, the band alignment edge must straddle the hydrogen and oxygen redox potentials. Third, the absorption spectral range should cover the entire solar spectrum (visible range), which leads to high photocurrent and solar-to-hydrogen efficiency. Finally, high chemical stability in the dark and under illumination is required. The electrolysis of water occurs according to oxidation and reduction half-reactions shown, respectively, in the following equations:

$$2H_2O + 4h^+ \rightarrow O_2 + 4H^+$$

$$4H^+ + 4e^- \rightarrow 2H_2$$

The overall reaction is expressed by

$$2H_2O \rightarrow 2H_2 + O_2$$

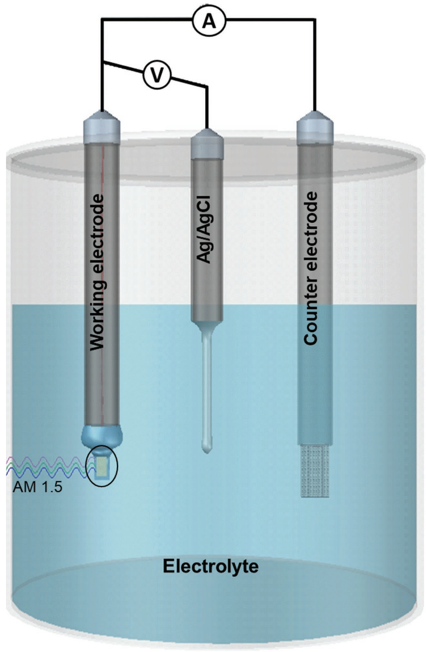


FIGURE 24.5 Experimental setup used for the PEC measurements, consisting of the working electrode, reference electrode (Ag/AgCI), and counter electrode (platinum coil) in one PEC cell.

Source: Obtained from the laboratory of PEC Technology at KACST.

PEC water splitting is one of the most promising solutions to the escalating energy demand and environmental issues. For decades, Honda and Fujishima demonstrated solar-driven PEC water splitting using an *n*-TiO_2 photoelectrode under UV light. Later, extensive research efforts focused on improving PEC water-splitting performance. For example, metal oxides such as TiO_2 (bandgap of 3.4 eV), $SrTiO_3$ (3.2 eV), and $KTaO_3$ (3.5 eV) have performed water splitting without extra bias. However, they have limited photon absorption under ultraviolet irradiation owing to a large band gap. The need for photoelectrodes with a narrow band gap to increase the absorption of a large proportion of the solar spectrum has driven the investigation of metal oxides, including iron oxide (Fe_2O_3), bismuth vanadate ($BiVO_4$), and tungsten oxide (WO_3). However, these oxide photoelectrodes are limited by higher applied biases owing to their poor electronic properties (Corby et al. 2018, Lee and Choi 2018, Ma et al. 2014, Pendlebury et al. 2014, Rai et al. 2014, Sotelo-Vazquez et al. 2017). Groups III–V semiconductor materials have excellent optical properties and band gap tunability, and they have held the record for solar-to-hydrogen conversion efficiency for decades. Nonetheless, they are unstable

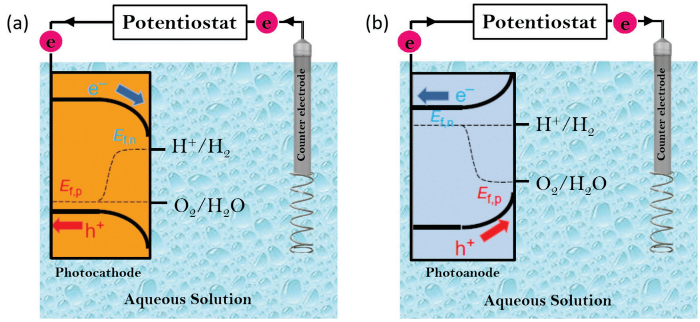


FIGURE 24.6 (a) Semiconductor/interface and (b) a single absorber semiconductor photocathode in contact with an electrolyte for water reduction. A single absorber semiconductor photoanode in contact with an electrolyte for water oxidation.

Source: Reproduced from Alqahtani (2019).

and corrode rapidly in alkaline or acidic electrolytes. The half-cell photoelectrode consists of only one absorber semiconductor, in which the single-absorber semiconductor photoelectrode can be either a photocathode or a photoanode for water oxidation or reduction, as shown in Figures 24.6(a) and 24.6(b). For semiconductor photoelectrodes to be practical, they should meet several requirements. In particular, they require a sufficiently narrow bandgap to harvest the solar spectrum and suitable band-edge potentials for water reduction or oxidation. In this context, the half-cell efficiency for water reduction and oxidation of a variety of Groups III–V semiconductor photoelectrodes have been widely reported.

At KACST, several photocatalysts have been studied and applied to produce green hydrogen using PEC water splitting, including carbon-based materials such as graphitic carbon nitride (GCN). GCN has gained considerable significance as one of the most suitable materials for large-scale photocatalytic water splitting because it has a narrow bandgap energy, PEC stability, non-toxicity, and low-cost production (Al Abass et al. 2021). GCN has been combined with reduced graphene oxide (rGO) and the resulting rGO/GCN nanocomposite has many advantageous characteristics for water splitting compared with bare GCN. First, it has higher absorption in the spectral visible region because of the uniform anchoring of GCN on the high surface area of the rGO sheets. Second, it has a higher separation rate of photogenerated charge carriers and more efficient migration of holes to the electrolyte owing to the interface interaction between rGO and GCN. Third, it has an improved adhesive nature due to the presence of rGO, enabling the uniform coating of the rGO/GCN nanocomposite on fluorine-doped tin oxide electrodes. This provides long-term stability and the easier transfer of electrons to such electrodes. As a result, the excellent performance of the water oxidation of the nanocomposite has been observed, with photocurrent density increasing by ninefold (approximately

90 mA cm^{-2}) compared with that produced by bare GCN under the same operating conditions (Al Abass et al. 2021). Simple, rapid, and high-purity methods have been developed, such as pulsed laser ablation of solids in liquids to fabricate different cheap catalysts and end with strong active working electrodes to split water efficiently. One of these catalysts is the ZnO/ZnSe nanocomposite, which exhibits excellent visible light-driven photocatalytic activity toward water-splitting applications (Al Abass et al. 2020). Moreover, many attempts have been made to replace charge carrier transport with other types of energy carrier transport mechanisms, such as hole quenchers, to improve insight into the mechanism (Al Abass et al. 2020, Zhao et al. 2019).

Hydrogen production using plasma technology

Plasma technology has shown promise for the production of hydrogen from different types of fossil fuels. Plasma technology can assist four mechanisms of hydrocarbon reformation: pyrolysis, partial oxidation, dry reforming, and steam reforming. However, the by-products of plasma reformation vary with the method employed and type of feedstock used. For instance, in the plasma pyrolysis of natural gas, the main products are hydrogen gas and carbon black (Fincke et al. 2002). By contrast, syngas (i.e., a mixture of CO and H_2) is the major product of the other methods of plasma reforming.

In general, plasma reformers are compact and can process a wide range of feedstocks (e.g., natural gas, heavy fuel oil, and solid waste), thus offering a high degree of flexibility. Plasma processes do not require catalyst addition or pretreatments of the feed gas. Hence, the processes are more resistant to the presence of sulfur within the feed gas in contrast to other conventional methods. Unlike conventional thermocatalytic processes that require preheating the catalyst, plasma technology offers a quick start-up and shutdown of reactors, which increases the levels of safety and automation. Therefore, plasma reformers can be considered the best option for producing hydrogen in different applications, from electricity generation to on-board fuel cell-powered vehicles (Bromberg, Cohn, and Rabinovich 1997).

Plasma can be classified as either thermal or non-thermal depending on the temperature of the electrons and heavier components (i.e., atoms, molecules, radicals, and ions; Tendero et al. 2006). For thermal plasma, the electrons and other species have similar temperatures; hence, it is termed an equilibrium plasma (Eliasson and Kogelschatz 1991, Tendero et al. 2006). The formation of thermal plasma requires high power densities, for example, from 100 W cm^{-3} to 10 kW cm^{-3} (Roth 2001). For non-thermal plasma, the electron temperature is much higher than that of heavier components, which remain between 300 and 1000 K (Tendero et al. 2006). The energy of non-thermal plasma electrons lies between 1 and 10 eV (Chen et al. 2008, Eliasson and Kogelschatz 1991, Tendero et al. 2006). Hence, these electrons have sufficient energy to break most of the chemical bonds. For instance, the mechanisms of methane reformation by plasma are normally initiated by electron impact reactions (Morgan 1992) followed by hydrogen abstraction by free radicals (Tsang and Hampson 1986):

$$CH_4 + e^- \rightarrow CH_3 + H + e^-$$

$$H + H \rightarrow H_2$$

$$CH_4 + H \rightarrow CH_3 + H_2$$

The performance of plasma reformers for producing hydrogen is normally affected by different operational parameters, including the composition of the feedstock, input power, and type of plasma discharge. The main challenges facing plasma reforming are the energy requirements in the form of electricity and carbon deposition in the reactor when employing the pyrolysis method. The latter could result in reactor plugging or reduce electrode activities and thus requires the electrodes to be cleaned regularly (García-Moncada et al. 2021, Indarto et al. 2008). Nevertheless, several studies have demonstrated the feasibility of using plasma technology to produce hydrogen and carbon black from natural gas. For example, in 2020, a commercial-scale plant was launched by Monolith Materials in Nebraska. The facility can produce 600 kg/h of hydrogen and 14 kT of carbon black.

KACST's R&D is focusing on the development of efficient plasma reformers for converting natural gas into hydrogen using two types of plasma reactors. These are a dielectric barrier discharge-packed bed plasma reformer and a gliding arc plasma reformer. These reformers are shown in Figures 24.7 and 24.8, respectively. This study includes developing selective dielectrics for hydrogen production and efficient discharge cell configuration to mitigate the negative effects of solid carbon production. The scope of this study also extends to the dry reforming of natural gas as a potential method for the conversion of CO_2 and methane gases into hydrogen-enriched syngas and other useful chemicals. Within the gliding arc plasma reformer, methane is cracked into hydrogen and black carbon, whereas in the presence of CO_2, methane can be converted into syngas:

$$CH_4 \rightarrow C + 2H_2$$

$$CO_2 + C \rightarrow 2CO$$

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2$$

Table 24.1 compares three common methods employed to produce hydrogen: SMR, plasma pyrolysis, and electrolysis. The table shows that hydrogen production from natural gas using plasma reformation avoids substantial CO_2 emissions, requires no catalyst addition, is unaffected by sulfur impurities, and is more power efficient than electrolysis methods.

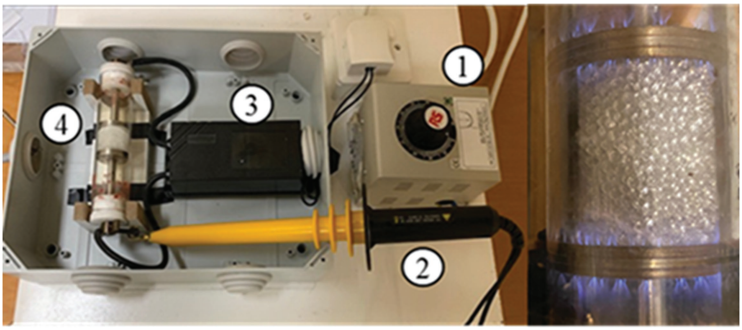
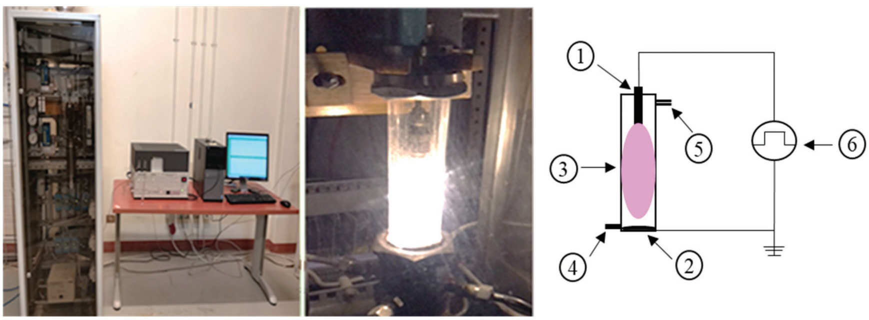


FIGURE 24.7 The dielectric barrier discharge-packed bed plasma reformer system employed for non-thermal plasma generation. The dielectric barrier discharge consists of a (a) voltage regulator, (b) HV probe, (c) high voltage power supply, and (d) discharge cell.

Source: Obtained from the laboratory of plasma technology at KACST.



(a) **(b)** **(c)**

FIGURE 24.8 (a) Gliding arc plasma reformer system; (b) the plasma discharge cell during the operation of the reformer; and (c) discharge cell consisting of (1) a high-voltage cathode, (2) anode, (3) plasma discharge, (4) feed gas inlet, (5) exhaust outlet, and (6) DC power supply.

Source: Obtained from the laboratory of plasma technology at KACST.

Hydrogen production from plastic waste using microwave-assisted reaction

One project of the KACST–Oxford Petrochemical Research Center is illustrating a one-step microwave-assisted reaction for the deconstruction of different types of plastic. The reaction takes only 30–90 seconds to transform the feedstock of commercial plastics into hydrogen and multiwalled carbon nanotubes. This one-step microwave-initiated process substantially simplifies the catalytic deconstruction of

TABLE 24.1 A comparison of approaches used to produce hydrogen

Parameter	*SMR*	*Plasma*	*Electrolysis*
CO_2 emissions kg/kg of hydrogen	12–14	0–0.8	0
Feedstock	Natural gas and steam	Natural gas	Deionized water
Catalyst requirement	Yes	No	Yes
Sulfur removal requirement	Yes	No	Yes
Power consumption (kW/kg hydrogen)	1–1.3	13	52
Hydrogen classification	Gray or blue*	Turquoise	Green

Note: *Hydrogen produced by SMR can be classified as blue if the process incorporates CO_2 capture.

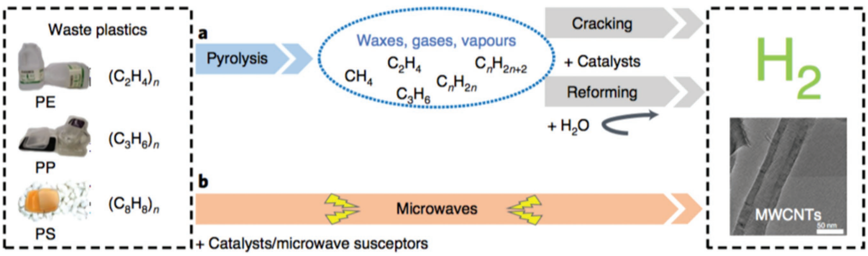


FIGURE 24.9 (a) Two-step pyrolysis and gasification process and (b) the present one-step microwave-initiated catalytic process (Jie et al. 2020).

Source: Reproduced with permission from Springer Nature.

plastic waste. Unlike in a two-step thermal pyrolysis, the microwave reaction rapidly transforms polyolefins into hydrogen fuel and multiwalled carbon nanotubes (Jie et al. 2020; Figure 24.9).

Different types of plastic waste such as milk containers (high-density polyethylene), plastic bags (low-density polyethylene), food wrapping (polypropylene), and plastic foam (polystyrene) are used in this project. A high hydrogen yield of 55.6 mmol g^{-1} was achieved with over 97% of the theoretical mass of hydrogen plastic extracted from the deconstructed plastic (Jie et al. 2020). Hydrogen efficiency is determined as the total mass of hydrogen contained in all the gas products compared with the theoretical amount of hydrogen contained in the starting plastic. There are different scenarios for the resulting carbon residue, one of which is hydrogenated, utilizing renewable hydrogen, or gasified into syngas, which can be subsequently recycled into waxes through the Fischer–Tropsch process (Dry 2008, Thomas and Thomas 2014).

Successful industrial microwave applications have been achieved in different areas, such as drying, heating, and sintering. However, scaling up microwave systems for an entire chemical process, such as the heterogeneous catalytic decarbonization reaction, is one of the greatest challenges. Given the various benefits that microwaves can provide, there are some difficulties in achieving the efficiency of the results, as at the bench scale. Several factors must be considered when scaling up the microwave process.

Penetration depth is a key parameter that defines the distance from the surface of the object under irradiation to the point at which the microwave power drops to 1/e of the applied power. Hence, microwave heating is a volumetric process. Any alteration in the magnitude of the chemical system results in a change in the microwave absorption properties of the sample. Thus, it is crucial to maintain the ratio between the system scale and power of the applied irradiation to avoid losing the benefits of microwave heating.

To achieve acceptable reproducibility by varying the microwave scale, the ability to control the reaction temperature is also essential. Moreover, the reaction pressure is another important factor because an increase in the reaction temperature increases the pressure. One of the proposed solutions is to install a proportional–integral–derivative temperature controller in the system.

When describing a single mode, the scaled-up applicator operates at lower frequencies (e.g., approximately 900 MHz). It is important to maintain the operation mode (i.e., field distribution within the applicator). When switching to a multimode system, the reactions can be conducted using parallel multivessel rotor systems at a lower frequency of 900 MHz. Overall, efficiency is significant compared with the size of the vessel, which can be enhanced when operating under continuous flow systems. This has clear and distinct advantages over batch reactors, especially when aiming to shift to industrial applications (Aldawsari 2017). In addition to the temperature control, a suitable microwave source and power supply must be selected. Furthermore, one advancement in the development of microwave systems is the utilization of a highly efficient solid-state microwave power source to enhance dehydrogenation processes.

Hydrogen production from water electrolysis

Water electrolysis, wherein solar energy from photovoltaic cells can be directly converted into hydrogen, has been extensively studied. Green hydrogen produced from renewable resources such as photovoltaic cells coupled with electrolyzers to split water can offer an attractive pathway toward sustainable energy. A typical alkaline electrolyzer has efficiency up to 70%. By contrast, the average working efficiency of PEM electrolyzers is approximately 80% and is expected to increase to 86% before 2030.

The major bottleneck for the widescale adoption of such green technologies is the development of cost-effective electrocatalysts that can efficiently reduce or oxidize water and produce hydrogen at a practical cost. That is, the higher price of green hydrogen than other types of hydrogen is mainly due to the high-priced materials used in electrolyzer cells. Precious metals such as Ru and Ir are the best-known catalysts for oxygen evolution reaction. The primary cost of an electrolyzer unit stems from the expensive materials used in its electrodes, which account for more than 60% of the system cost. Numerous research efforts have been made toward finding new earth-abundant electrocatalytic materials to enhance the hydrogen and oxygen evolution reactions. Researchers at KACST have explored the potential use of metal oxides or materials to replace the precious metals used in electrolyzers. This entails finding new materials and techniques to improve electrocatalytic activity. The primary thrust of this research activity is to identify and optimize an ideal catalyst that can meet the international hydrogen target at both the material and the system levels. Two approaches are considered: synthesizing new suitable metal oxide catalysts and optimizing promising catalysts. When adopting this approach, it is important to develop efficient catalysts using abundant metals such as Co and Ni. The surface charge properties, including band bending, can be engineered by incorporating metal nanoparticles with different work functions on the catalyst surface. In addition to enhancing charge separation and extraction, the catalyst can reduce the overpotential for water oxidation.

Graphene, a 2D network of sp2-hybridized carbon atoms with a hexagonal structure, is a potential earth-abundant material under investigation at KACST as an electrocatalyst for water reduction. It possesses excellent properties such as high conductivity (106 Scm^{-1}), high mobility (200,000 $cm^2\ V^{-1}\ s^{-1}$), a large theoretical specific surface area (2630 $m^2\ g^{-1}$), and excellent optical transmittance (~97.7%). These properties allow charges to easily migrate through graphene, such as in the water reduction reaction; hence, graphene can be used as an electron acceptor and transporter.

Other earth-abundant electrocatalysts have also been extensively explored at KACST. Transition metals such as Fe, Co, and Ni are vital resources that can be used as effective electrocatalysts. Additionally, the 2D material molybdenum disulfide (MoS_2) has abundant catalytic edge sites with a high surface energy, making it an efficient catalyst. The drawback of MoS_2 is that its charge mobility is inherently highly anisotropic. Transport along the S-Mo-S layers is relatively rapid (approximately 200 $cm^2\ V^{-1}\ s^{-1}$), whereas that perpendicular to the S-Mo-S layers is three-fold lower. However, this limitation can be overcome by reducing the distance that charge carriers must travel to the electrode surface, as in nanostructured MoS_2. In addition to these materials, such oxygen evolution electrocatalysts as Co_3O_4, NiOOH, dual-layer Fe/NiOOH, Co-Bi, Co-Pi, and Ni-Bi can be used to improve the slow hole transfer kinetics in water oxidation.

In short, metal electrocatalysts generally allow for enhanced current and improved onset potential and stability. However, the particular traits and performance of a given metal electrocatalyst are distinct and depend on the synthesis method. Likewise, the overall performance of electrodes is largely governed by their interface properties. Therefore, it is extremely important to develop and synthesize earth-abundant metal nanoparticles for water electrolysis applications. It is also necessary to understand the interface to further optimize the electrocatalyst/liquid junctions and, more importantly, control the catalytic activity and stability at the surfaces of the electrode in contact with the electrolyte.

Alternatively, two main techniques have been used to improve the performance of promising nanomaterial-based electrodes. The first is enhancing electron charge carrier migration by improving and optimizing material quality, doping, and photoelectrode morphology. The second is optimizing the electrode–electrolyte interface charge kinetics using efficient electrocatalysts and engineering their surface properties.

For the system implementation, modeling, and simulation of device parameters and material properties, KACST has developed benchmarking, testbed architectures, and testbed prototypes to study material performance under real reaction conditions. Rapid testbed prototyping enables validating the performance of the synthesized electrocatalysts and photocatalysts in real-time conditions. This enables the improvement of system durability, robustness, and lifespan. A testbed prototype also allows for a more accurate economic assessment.

Case study

The KACST's mission is to advance R&D on emerging clean hydrogen production technologies. In the early 2000s, intensive R&D activities were conducted on PEM fuel cells. R&D has focused on developing materials for catalytic reactions and membranes. These activities have led to several publications and IPs. At the industrial level, KACST has begun to develop solid oxide fuel cells (SOFCs) with international partners. SOFCs convert natural gas (i.e., CH_4) into hydrogen, which can be used to generate electricity. KACST has established facilities for the assembly and testing of SOFCs. A pilot project between KACST and the Saudi Electricity Company (SEC) has been established to test the efficiency of the developed SOFC technology as a power generation system at an industrial site. In addition, the project aims to develop and identify general applications of this technology in the power generation sector. From 2018 to 2020, several fuel cells that generate electricity were tested at the SEC's Power Plant No. 9 in Riyadh to produce power with a steady efficiency of approximately 61%. Figure 24.10 illustrates the fuel cell system testing facility at the SEC's Power Plant No. 9 in Riyadh.

Conclusion

Saudi Arabia has already formulated short- and long-term strategies to achieve its goal of net-zero CO_2 emissions. Many domestic companies and research institutes are conducting R&D into the production and utilization of clean hydrogen fuel to

FIGURE 24.10 SOFC system testing facility at the SEC's Power Plant No. 9 in Riyadh.
Source: Authors.

support these national strategies. KACST's focus on green hydrogen production began in the 1980s. It has explored innovative and alternative ways to produce CO_2-free hydrogen from fossil fuels using the microwave heating of heterogeneous catalysts. In the area of green hydrogen, KACST has developed efficient and low-cost catalysts for producing hydrogen via the electrolysis process to make alloys with non-noble metals (e.g., Cu-based) or alloys with the low loading of noble metals (3.28 wt% of Pt nanoparticles). In addition, KACST has been developing solar-driven PEC water splitting as well as efficient plasma reformers for converting natural gas into hydrogen. Furthermore, KACST, in collaboration with various research, development, and innovation ecosystem stakeholders, has proposed a comprehensive clean hydrogen production and utilization strategy as a roadmap to address outstanding R&D gaps. The program aims to overcome the challenges and exploit the opportunities across the clean hydrogen production and utilization innovation value chain.

Abbreviations

EISA	Evaporation-induced self-assembly
GCN	Graphitic carbon nitride
KACST	King Abdulaziz City for Science and Technology
NEB	Net energy balance
PEC	Photoelectrochemical
PEM	Proton exchange membrane
rGO	Reduced graphene oxide
SEC	Saudi Electricity Company
SEM	Scanning electron microscope
SMR	Steam methane reforming
SOFCs	Solid oxide fuel cells
TEM	Transmission electron microscopy

Note

1 The bandgap is the distance between the valence band of electrons and conduction band.

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25

HYDROGEN PRODUCTION USING NUCLEAR ENERGY

Abdulrahim Al Judaibi, Sharaf AlSharif and Saleh Al Harbi

Why use nuclear energy to produce hydrogen

Nuclear energy is produced in reactors by splitting the nuclei of atoms. The energy released from nuclear reactions is much greater than the energy from chemical reactions. For example, 1 kg of uranium-235 produces 2–3 million times more energy than what is produced from burning 1 kg of coal. Therefore, nuclear power is considered an efficient energy source.

Because nuclear reactors do not emit greenhouse gases (GHGs) during operation, they could be defined as a clean energy source, where "clean" is used to imply that no GHGs are directly emitted. Nevertheless, the carbon footprint of a nuclear power plant increases when considering the entire life cycle of the plant, including indirect GHG-emitting stages such as fuel mining and plant construction. However, nuclear power plants operate for over 60 years, and the initial carbon footprint becomes insignificant when averaged over the reactor's life cycle.

A recent study compared the carbon footprint of nuclear energy with variable renewable energy (VRE) sources such as wind and solar. It found that the average CO_2 emissions over the life cycle for nuclear, wind, and solar energy are 14, 17, and 42 g of CO_2 per kWh, respectively. Other studies have obtained similar findings (Schlömer et al. 2013, Pehl et al. 2017).

Although the levelized cost of electricity is higher for nuclear energy than for VRE (Ram et al. 2018), nuclear power plants produce hydrogen at a cost 70% below that of VRE (Acar and Dincer 2014). Nuclear plants can also provide reliable power with a capacity factor above 90% for continuous hydrogen production. Comparably, the intermittency of VRE, which has capacity factors below 40% (Suman 2018), means that hydrogen production fluctuates with their intermittency. Therefore, nuclear energy can achieve a higher daily

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hydrogen production rate and enables coupling the power plant to a centralized high-volume hydrogen production facility.

There are 433 nuclear power reactors in operation globally, providing a combined electrical capacity of approximately 388 GW (PRIS 2022) and producing 10% of global electricity at 2,653 TWh in 2021, a 4% increase from 2020 (World Nuclear Association 2022a). Nuclear power produces 25% of clean energy worldwide (IEA 2021), and 30 more countries are planning to introduce nuclear power to their energy mix to meet their climate goals (World Nuclear Association 2022b). Currently, 52 power reactors are under construction in 19 countries, which, once finished, will supply an additional 14% of combined capacity to increase total capacity to 442 GW.

Many advanced reactors are being developed with hydrogen production facilities designed to be directly coupled to nuclear power plants. Advanced nuclear reactors may operate their primary coolant cycles at higher temperatures, up to 1000°C. The primary cycle can be used to heat steam to high temperatures in a separate coolant cycle that directly feeds the hydrogen production facility. This eliminates the need to electrically heat the steam, which in turn improves the overall efficiency of the system and reduces costs.

Nuclear energy strategy in Saudi Arabia

To diversify its energy mix and reach net-zero emissions in accordance with the objectives of Saudi Vision 2030, Saudi Arabia is planning to introduce nuclear power to its energy mix by constructing two large nuclear power plants. The country is striving to diversify its economy and enhance its international position in multiple fields. Therefore, the application of nuclear energy is considered a future potential enabler that would accelerate the Kingdom's technological and industrial development as well as its economy. The implementation of a well-structured nuclear program is also expected to enhance the development of other national sectors.

King Abdullah City for Atomic and Renewable Energy was established by Royal Order on April 17, 2010. Its aim is to build a sustainable energy future for Saudi Arabia by developing substantial alternative energy capacity. The Saudi National Atomic Energy Project (SNAEP) is consistent with the Kingdom's international obligations and national policy of adopting nuclear technologies for energy development and production. The SNAEP includes works, activities, and projects implemented in an integrated manner. These include developing a national nuclear infrastructure, building the first nuclear power plant, expanding human and local content capabilities, and exploring the potential of emergent technologies, notably hydrogen production (Figure 25.1).

Saudi Vision 2030 targets sustainable power production that maintains the Kingdom's status as a leader in the energy field. One essential benefit of introducing nuclear energy is to diversify energy sources rather than completely rely on oil and its products for power production. This will maximize the utilization of oil

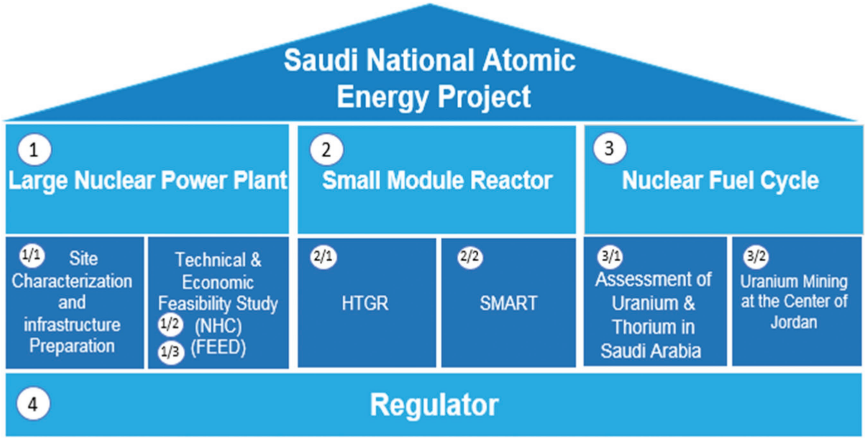

FIGURE 25.1 Saudi National Atomic Energy Project (SNAEP) Components. Note: FEED = front-end engineering design; HTGR = high-temperature gas-cooled reactors; SMART = small integrated nuclear reactors.

resources for more value-added applications for future generations. In addition, as a part of the Saudi net-zero targets by 2060, nuclear energy will play a key role in achieving the net-zero goal.

In addition to electricity generation, nuclear power may mitigate the water scarcity problem by expanding its use in the desalination of seawater. This will positively impact Saudi citizens and many sectors in the Kingdom, such as the agricultural and industrial sectors. Desalination using nuclear power can also reduce the carbon footprint of desalination plants. An advantage of this approach is the creation of new and broad job opportunities of an advanced technical nature. Besides its plan to introduce nuclear energy to generate electricity, Saudi Arabia is also exploring other applications, such as the opportunity to produce pink hydrogen (i.e., hydrogen produced using nuclear power).

Using nuclear technologies to produce hydrogen

Hydrogen is a clean fuel source because it releases water when burnt (Poizot and Dolhem 2011). However, its reputation as clean is tainted by the fact that over 95% of hydrogen production comes from fossil fuels (Wang and Zhang 2017). Hence, while nuclear and renewable energy sources may produce hydrogen without emitting GHGs, the production method used should also be considered.

The most common production method is steam methane reforming (SMR; Holladay et al. 2009), which produces 0.3–0.4 m^3 of CO_2 per m^3 of hydrogen (Muradov 2001) or around 35% of the hydrogen produced by volume. However, SMR produces 7 kg of CO_2 for every 1 kg of hydrogen produced (Soltani, Rosen, and Dincer 2014). Although SMR can be coupled with carbon capture, usage, and storage, which is assumed to reduce CO_2 emissions by as much as 90% (BEIS 2021), it would still lead to significant releases during large-scale production. However, SMR is economically favored over other clean production methods because of its relatively low cost. For that reason, it accounts for over 50% of the hydrogen produced worldwide (IAEA 2018).

Alternative clean methods that split water into its constituents (i.e., hydrogen and oxygen) without releasing other by-products can be used instead of SMR. There are three methods for splitting water: thermal energy (thermolysis), electrical energy (electrolysis), and thermochemical processes. The thermolysis of water is impractical because it requires temperatures over 2500°C, which current materials cannot endure for a long period of operation. Conversely, electrolysis can be performed at room temperature, and the thermochemical cycles range from 500°C to 2000°C. A combination of the two is also possible as hybrid cycles, which can reduce the electrical energy required and therefore the cost.

Electrolysis

Electric energy can be used to split water molecules into hydrogen and oxygen. Electrolysis is a well-developed method used for many commercial applications; however, it accounts for only approximately 5% of the world's commercial hydrogen production (IAEA 2018). The main limiting factor is the cost of electricity.

High-Temperature Steam Electrolysis (HTSE)

The cost of electrolysis can be reduced by using heated steam instead of liquid water, which reduces the electrical energy required to split water into hydrogen and oxygen. The efficiency of HTSE can also be practically increased by up to 90% using solid oxide electrolysis cells (SOEC) as the steam temperature increases (Xu, Dong, and Ren 2017). However, this efficiency represents only the efficiency of the electrolyzer. Total efficiency must include the efficiency of steam heating as well as electric power generation.

Nuclear reactors improve overall efficiency because they already operate at high steam temperatures that can be directly routed to a hydrogen production facility. Overall efficiency is improved even further when the reactor is designed to operate at temperatures above 600°C owing to the direct steam heat provided. Moreover, operating at higher temperatures increases the power generation efficiency. Conventional nuclear reactors have a power generation efficiency of approximately 33%, whereas advanced high-temperature reactors have an efficiency of up to 52%.

Thermochemical processes

Water splitting can be achieved without using electrical energy if the thermal energy is sufficiently high. Indeed, water starts to divide into its constituents at temperatures above 2,500°C. Since these extremely high temperatures are impractical, a solution to this problem was developed using chemical reactions that enable water splitting at lower temperatures. The chemical reactions consist of water and recyclable chemical compounds that form a cycle that does not release any by-products. Only feed water is supplied to the cycle and is then split into hydrogen and oxygen.

Several thermochemical cycles featuring various chemical compounds had been developed in the 1970s. The range of temperatures at which well-researched cycles operate is between 500°C and 1,000°C. An advantage of these methods is that they reduce costs by not relying on electricity. However, the challenge is to transition these cycles from the research level to the commercial industrial scale and engineer materials that sustain long-term high-temperature operations in a corrosive environment.

Sulfur-iodine cycle

The sulfur-iodine cycle is a thermochemical cycle that consists of a three-step reaction operating at a maximum temperature of 850°C (Figure 25.2). The efficiency of this cycle is approximately 50%. An advantage of this method is that all the chemical components are in the fluid state, either as liquid or as gas. Large-scale production feasibility is still limited, mainly because the sulfur-iodine cycle uses highly corrosive compounds such as sulfur dioxide and hydroiodic acid.

The General Atomics EM^2 reactor provides the highest coolant outlet temperature among the reactors that have progressed beyond the conceptual design stage. It is also the design with the highest efficiency (53%) owing to its high coolant temperature of 850°C. General Atomics has produced hydrogen for the US Army

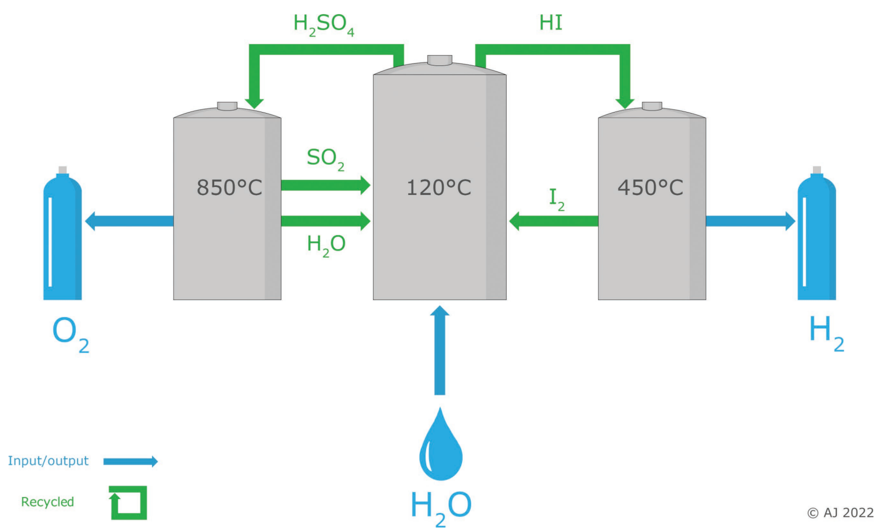

FIGURE 25.2 Sulfur-iodine thermochemical cycle.

after it successfully demonstrated hydrogen production in its aluminum power system (ALPS), which was developed as a portable non-nuclear battery. Aluminum is considered the third-best source of chemical energy based on volume. The energy density of aluminum is 23.3 kWh/L. Chemical energy is a much smaller source of energy compared with nuclear energy. In fact, the energy density of aluminum is over 15 million times lower than that of uranium. The energy density of uranium is approximately 400,000,000 kWh/L.

Although General Atomics holds proprietary rights for its ALPS and aluminum cycle, it conducted studies (Brown et al. 2003) in collaboration with Sandia National Laboratory and US universities (World Nuclear News 2021). Its findings led it to recommend the use of the sulfur-iodine cycle owing to its high efficiency and good economics. The study estimated a hydrogen production cost of approximately USD 2.10 after adjusting for inflation to 2021 USD.

Hybrid sulfur cycle

The hybrid sulfur cycle consists of a two-step reaction: thermochemical (approximately 850°C) and electrochemical (electrolysis). This is shown in Figure 25.3. Its efficiency is similar to that of the sulfur-iodine cycle (approximately 50%). The hybrid sulfur cycle reduces the required electrolyzer cell potential by 87% and removes iodine from the sulfur-iodine cycle, which eliminates possible corrosion by hydroiodic acid. However, it shares challenges similar to those of the sulfur-iodine cycle method because sulfur dioxide corrosion remains a problem that requires the development of resistant materials.

The Canadian-based company Terrestrial Energy is developing an integral molten salt reactor (IMSR) with a focus on feasible hydrogen production. Terrestrial has partnered with US laboratories to develop a hybrid sulfur cycle to produce

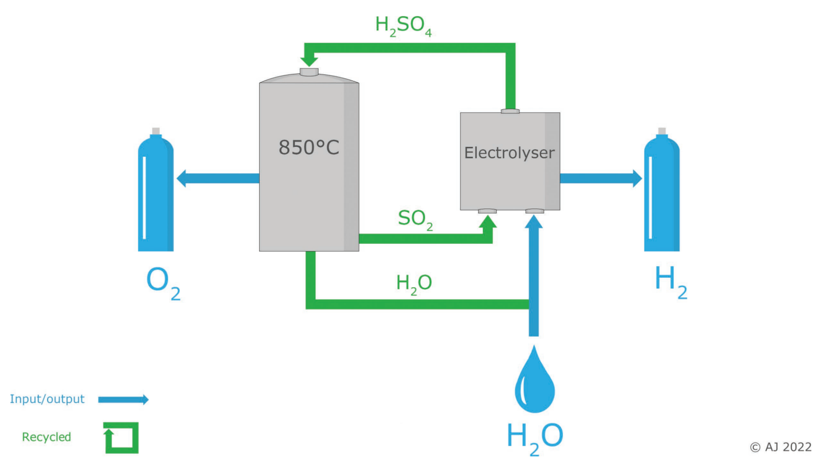

FIGURE 25.3 Hybrid sulfur electro/thermochemical cycle.

hydrogen in the IMSR. The hybrid sulfur cycle method splits water in two steps. The first step is a thermochemical reaction that requires temperatures over 850°C. The second step is an electrochemical reaction that consumes a 10-fold lower electrical potential than conventional electrolysis.

Hybrid sulfur cycle research in the United States has been funded by the Department of Energy (DOE) as a part of its solar thermochemical hydrogen research program (Gorensek, Corgnale, and Summers 2017). After the completion of the program, the DOE allocated funding for hybrid sulfur cycle development in the IMSR in partnership with national laboratories and utility companies (Savannah River National Laboratory 2020). The target hydrogen production cost in the IMSR is USD 2/kg. For comparison with non-nuclear sources, the European Commission's hydrogen strategy (EU Commission 2020) states that the estimated hydrogen production cost from fossil fuels is USD 1.76/kg. In addition, the production cost using renewable energy in Europe is estimated to be above USD 3/kg.

Copper-chlorine cycle

The copper-chlorine cycle is a hybrid cycle consisting of three to five steps depending on the processes applied (Figure 25.4). It requires a maximum temperature of 550°C, lower than that required for the sulfur-iodine and hybrid sulfur cycles; however, it also has lower efficiency (43%). The main advantage is that it operates

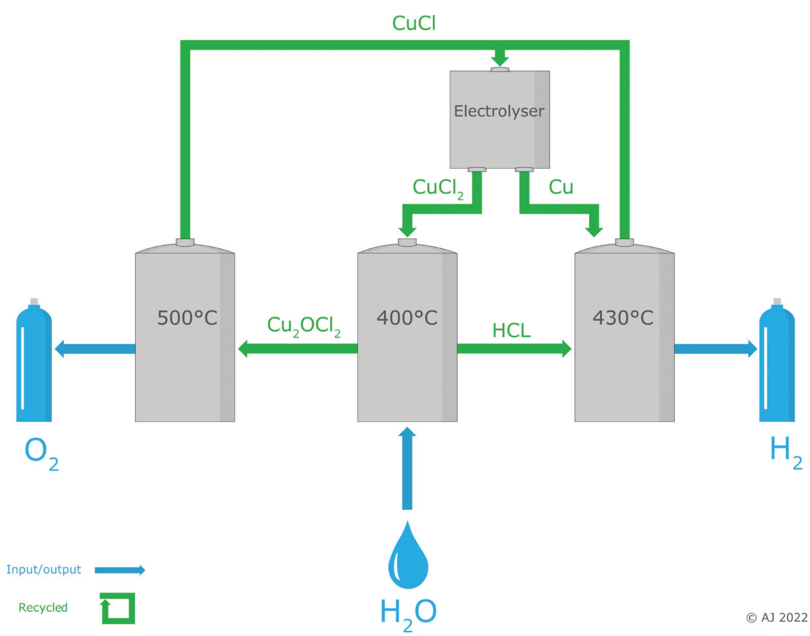

FIGURE 25.4 Copper chlorine (Cu-Cl) four-step hybrid cycle.

at a lower temperature than what many advanced reactors are designed to provide. The drawback is that some copper-chlorine cycles contain solid copper particles in one of the steps; however, this is solved in the four-step cycle.

Comparative analysis of hydrogen production methods

The technology readiness level (TRL) and economic and environmental aspects are analyzed to compare hydrogen production methods that could be coupled to nuclear power plants. Although many more production methods exist, the focus is narrowed to the most developed clean production methods close to near-term deployment. The comparison also includes SMR, which serves as a baseline reference because it is the most widely used commercial production method. While SMR is not a clean method, it can be improved when carbon capture is used.

Technology readiness level

The production of hydrogen using nuclear energy has been of great interest since it first gained traction after the 1973 oil crisis. However, R&D slowed down with the decline in interest in nuclear power after the Chernobyl accident in 1986. In recent times, R&D activities to generate alternatives to fossil fuels and reduce GHG emissions have gained importance globally.

The TRLs used in this analysis are based on the expected period until commercial production (Pinsky et al. 2020). Near-term deployment indicates that the technology is expected to be deployed within five years. Medium-term deployment is expected to range between 5 and 10 years. Long-term deployment is expected to require more than 10 years. The TRL is used to describe the extent of development necessary to reach commercialization. It ranges from theoretical principles at TRL 1 to operational plants at TRL 9.

Most hydrogen produced commercially is employed in industrial applications, mainly in the hydrocarbon industry, where it is used to refine petroleum. Conventionally, the hydrocarbon industry is inclined to use cheap, maintainable, and readily available production methods. Methane gas is the simplest hydrocarbon compound and it can be extracted from natural gas on site. Indeed, SMR is the most mature and most developed method for producing hydrogen in the hydrocarbon industry.

The most developed clean production method is water electrolysis, which is commercially available using either alkaline technologies or polymer electrolyte membrane (PEM) electrolyzers. Both methods use liquid water and depend solely on electrochemical splitting. The efficiency of the PEM is slightly higher than that of alkaline methods; however, its cost is also higher. As discussed earlier, the efficiency of both methods can be increased by using steam instead of liquid water. Thus, research is underway to develop high-temperature electrolysis (HTE) techniques, with SOEC being the closest to commercial production. Thermochemical cycles such as the sulfur-iodine, hybrid sulfur, and copper-chlorine cycles are all expected to require more than 10 years for commercial utilization. This is because much research is needed to solve the challenges related to the durability of the materials used in these cycles (Table 25.1).

Cost and carbon footprint estimation

The cost of producing clean hydrogen remains one of the main challenges to its commercial feasibility, as current methods such as SMR are cheap, mature, and reliable. Therefore, this analysis considers CO_2 emissions to highlight the cost-to-emission performance of the production methods. Parkinson et al.'s (2019) comprehensive analysis compares the production cost and average CO_2 emissions over the life cycle of hydrogen production methods. Table 25.2 summarizes their results into three estimation levels for both the production cost and emissions.

The electrolysis method used in this analysis is PEM electrolyzers for wind, solar, and nuclear power. However, it would be interesting for future work to analyze SOEC and HTE to compare their performance and potential improvements. Further, the

TABLE 25.1 TRLs of hydrogen production methods

Hydrogen production method	*Temperature required (°C)*	*Readiness level*
SMR	700–1,000	9
Electrolysis using water (alkaline)	20–100	9
Electrolysis using water (PEM)	20–100	6
Electrolysis using steam (SOEC)	>700	5
Sulfur-iodine cycle	850	4
Hybrid sulfur cycle	850	3
Copper-chlorine cycle	550	3

Source: Pinsky et al. (2019).

TABLE 25.2 Hydrogen production costs and carbon footprints of alternative production methods

Production method	*Production cost (USD per kg of hydrogen)*			*CO_2 emissions (kg CO_2 per kg of hydrogen)*		
	Low	*Central*	*High*	*Low*	*Central*	*High*
SMR	1.0	1.3	2.2	10.1	13.2	17.2
SMR with carbon capture	1.9	2.1	2.3	3.0	5.6	9.2
Electrolysis using wind power	4.6	7.9	10.0	0.5	0.9	1.1
Electrolysis using solar power	7.1	12.0	14.9	1.3	2.2	2.5
Electrolysis using nuclear power	5.0	6.8	8.2	0.5	0.8	1.0
Sulfur-iodine cycle	1.5	1.8	2.7	0.4	1.2	2.2
Copper-chlorine cycle	1.5	2.1	2.7	0.7	1.1	1.8

Source: Parkinson et al. (2019).

thermochemical cycles are estimated to potentially provide cost-competitive clean hydrogen compared with SMR. Although the hybrid sulfur cycle is excluded from the study, its performance is predicted to be similar to that of the sulfur-iodine cycle.

Nuclear reactor technologies for producing hydrogen

Conventional nuclear power plants can provide emission-free electricity to power a PEM electrolyzer at a cost of approximately USD 7/kg of hydrogen. If SOEC electrolyzers are used, the cost is estimated to be approximately USD 3.5/kg, and if thermochemical cycles are used, it was estimated to be roughly USD 2/kg. However, conventional nuclear power plants operate at a lower temperature (around 330°C) and therefore must include a heating stage to deliver the high-temperature steam feed required by SOEC and thermochemical cycles. Advanced reactor designs such as high-temperature gas-cooled reactors (HTGRs) can provide temperatures up to 1,000°C. They can directly exchange the heat from the reactor's secondary coolant cycle with a hydrogen production facility. Table 25.3 shows some examples of advanced reactor technologies for producing hydrogen.

High-temperature gas-cooled reactors

HTGRs are the most developed Generation-IV advanced reactor design and are the first Gen-IV reactors to be demonstrated. HTGRs are designed to operate at temperatures above 750°C using gas coolants such as helium. While the primary coolant outlet temperature of some HTGR designs is 750°C, the steam outlet temperature in the secondary cycle is only 566°C (World Nuclear News 2021).

HTGRs can produce hydrogen using three methods: HTE, SMR, and the sulfur-iodine cycle. SMR directly produces CO_2 as a by-product. Therefore, only HTE and the sulfur-iodine cycle are considered to be green unless SMR is coupled with carbon capture technologies. HTE could use a solid oxide electrolyzer that provides relatively high conversion efficiency depending on the feed temperature. For example, the HTE method can theoretically provide overall efficiency of up to 80%. While the sulfur-iodine cycle is considered a potential method, the manufacturer must address the need for materials that can mitigate possible corrosion and an aggressive chemical environment.

TABLE 25.3 Primary coolant outlet temperatures and estimated deployment period of advanced reactor designs.

Advanced reactor design	*Coolant temperature (°C)*	*Estimated deployment period*
HTGRs	>750	Near term
GFRs	>850	Long term
MSRs	~700	Medium term

Source: Authors.

The United States has supported the development of nuclear hydrogen systems with HTGRs. In August 2021, a group of students competed in a competition conducted by the Nuclear Energy Agency for reactor innovation. The competition was won by a team of students who considered hydrogen production in an HTGR using the copper-chlorine cycle connected to an existing coal gasification plant. The suggested site was Athabasca oil sand in Alberta. The first Generation-IV reactors started operations when China opened its HTGR demonstration plants at the end of 2021.

Gas-cooled fast reactors (GFRs)

GFRs are similar to HTGRs as both use gas as a coolant. GFRs, however, have been designed to operate at higher temperatures and thus can achieve higher efficiencies. The higher operational temperatures require the development of advanced materials that can sustain the thermal load. Nevertheless, GFRs could provide very high temperatures once developed. There are currently a handful of companies with GFR designs under development and the design approach tends to favor higher efficiency because GFRs are unique in that they could operate a closed Brayton cycle where the primary coolant is directly connected to the turbine. Such designs would require further development to facilitate heat exchangers for steam generation if hydrogen production is favored.

Molten salt reactors (MSRs)

MSRs are advanced reactors that use molten salts as coolants instead of water or gas. Molten salts can hold high temperatures at around 700°C, which are feasible for HTE and thermochemical cycles such as copper-chlorine. MSRs are yet to be deployed commercially but they have seen significant development in the last couple of years. Several companies worldwide have developed conceptual designs of various MSR technologies that differ in aspects such as fuel, coolants, size, power capacity, and among other things. The one feature that MSRs share in common is the ability for molten salts to operate at higher temperatures. Therefore, most of the existing MSR designs consider hydrogen production in their reactors, in particular using the sulfur cycles. These reactors have been gaining popularity as well as funding from both public and private sectors, and as mentioned previously for the case of IMSR technology, funding for hydrogen production research.

Conclusion

The most developed clean hydrogen production method is water electrolysis, which is commercially available using either alkaline technologies or PEM electrolyzers. Nuclear energy is deemed a clean energy source, and it could play a pivotal role in Saudi Arabia's future clean hydrogen production. Current nuclear reactor technologies could be used to produce hydrogen but at a high cost compared to alternative clean energy sources such as wind and solar. However, advanced nuclear reactors are being developed with increased efficiency and economics, and since nuclear reactors do not suffer from the intermittency of renewable energies, they can provide high-temperature steam for continuous hydrogen production. As Saudi Arabia plans to introduce nuclear energy to its electric energy mix, it is also exploring the opportunity to produce pink hydrogen using nuclear technologies.

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26

PRODUCTION, CRACKING, AND USE OF GREEN AMMONIA TO SUPPORT THE HYDROGEN ECONOMY

Omar Behar, Saumitra Saxena, Deoras Prabhudharwadkar, Bassam Dally and William Roberts

Introduction

Hydrogen can be used to store, move, and deliver the energy produced from other sources. Some scenarios predict the use of hydrogen in up to 50% of end-use demand applications by the end of the 21st century (Valera-Medina et al. 2021). However, the creation of such a 'hydrogen economy' faces several constraints that require the development of equipment and infrastructure.

The storage and transport of hydrogen, a very light molecule, can be manifold more expensive than that of common gaseous and liquid fuels. Different approaches have thus been proposed to chemically bond hydrogen with other molecules such as ammonia (NH_3), Methanol-water ($CH_3OH–H_2O$), and cycloalkanes. Alternatively, it can be stored in the hydrides of lightweight elements (e.g., boron, nitrogen, and carbon) and physisorbents (e.g., metal–organic and covalent organic frameworks).

Ammonia is a notable frontrunner as a hydrogen carrier because its storage is cheaper than that of hydrogen (The Royal Society 2020, Salmon and Banares-Alcantara 2021). The International Energy Agency estimates a storage-related CAPEX of $90,000 per tonne of liquid hydrogen compared with only $11,000 per tonne of hydrogen if stored as ammonia (Salmon and Banares-Alcantara 2021). Other barriers to hydrogen storage and transport include its high diffusivity, low energy volumetric density, high flammability range, and the embrittlement of certain metals. All these factors exacerbate the challenge of transporting hydrogen for use as a zero-carbon fuel; hence, an alternative is needed (Valera-Medina et al. 2021).

Ammonia has great potential as a hydrogen carrier, particularly in the transition toward a hydrogen economy (U.S. Department of Energy 2015). Liquid ammonia has a greater volumetric hydrogen density than liquid hydrogen itself (107 kg of hydrogen per m^3 of liquid; Djinović and Schuth 2015). Further, ammonia is

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a zero-carbon molecule that can be stored under relatively moderate conditions (i.e., refrigerated at −33°C at atmospheric pressure or at 0.8–1.0 MPa) under atmospheric temperature (U.S. Department of Energy 2015). The versatility of this molecule has therefore led to its distribution at commercial and global scales. According to the US Geological Survey, the global production of ammonia in 2019 reached 182 million metric tonnes, more than double the quantity of hydrogen gas produced in the same year (Liu and Sartori 2020). Therefore, large-scale infrastructure is available for the immediate implementation and further expansion of an 'ammonia economy' in support of a futuristic 'hydrogen economy' (Valera-Medina et al. 2021). Indeed, fossil fuels are the primary feedstock for producing ammonia. However, ammonia is an excellent proposition for converting renewable energy (particularly solar and wind) to hydrogen and then to ammonia, transporting it to locations with low renewable energy intensity, and converting the ammonia back to hydrogen for local consumption (Giddey et al. 2017).

In Saudi Arabia, three companies, Air Products, ACWA Power, and Neom, have signed an agreement to construct and operate a production facility powered by 4 gigawatts (GW) of wind and solar renewable energy for the production and export of green ammonia to global markets (Ammonia Energy Association 2020). Green ammonia will be used for transportation. On the contrary, the German government considers green hydrogen, produced by electrolyzing water, to be the only sustainable production technology in the long term, with ammonia used as a hydrogen carrier (Salmon and Banares-Alcantara 2021). Therefore, the idea of producing green ammonia in Saudi Arabia and exporting it to countries such as Germany and Japan is of particular interest. This chapter focuses on the production of ammonia as a transport vector for solar energy and its subsequent reconversion to hydrogen at its export destination.

Producing green ammonia using solar energy

Basic concept

Unlike brown and gray ammonia, which are made using fossil fuels as the feedstock, the raw materials for green ammonia are hydrogen. This is obtained through the electrolysis of water, and nitrogen, obtained from the air using an air separation unit (ASU). Figure 26.1 illustrates a typical green ammonia synthesis process. Hydrogen and nitrogen gases are produced, compressed to the required pressure, and fed to the Haber–Bosch reactor. This produces ammonia in the presence of an iron oxide catalyst (Lipman and Shah 2007). The reaction is typically carried out over iron catalysts at temperatures of 400–600°C and pressures of 200–400 atm (U.S. Department of Energy 2015). The required electricity can be generated using commercially available solar power technologies, including solar photovoltaic (PV), concentrated solar power (CSP), and hybrid technologies such as PV-CSP and PV-wind.

Figure 26.2 depicts a typical hybrid PV-CSP power plant. The CSP unit is based on commercial molten-salt central receiver technology. It consists of a heliostat

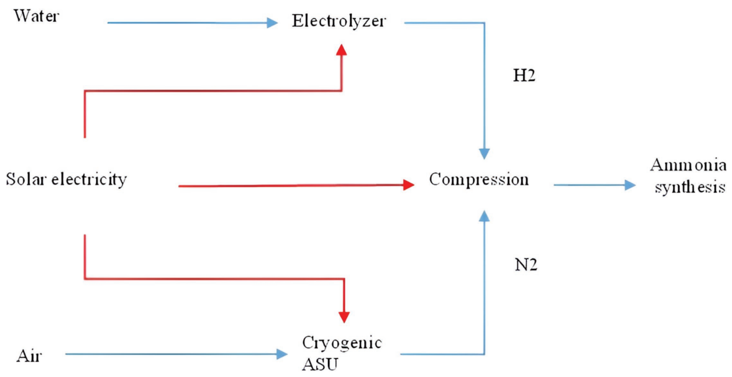

FIGURE 26.1 Production process of green ammonia (blue lines: fluid, red lines: electricity). The raw materials for green ammonia are hydrogen, obtained through the electrolysis of water, and nitrogen, obtained from the air using an ASU.

Source: Authors.

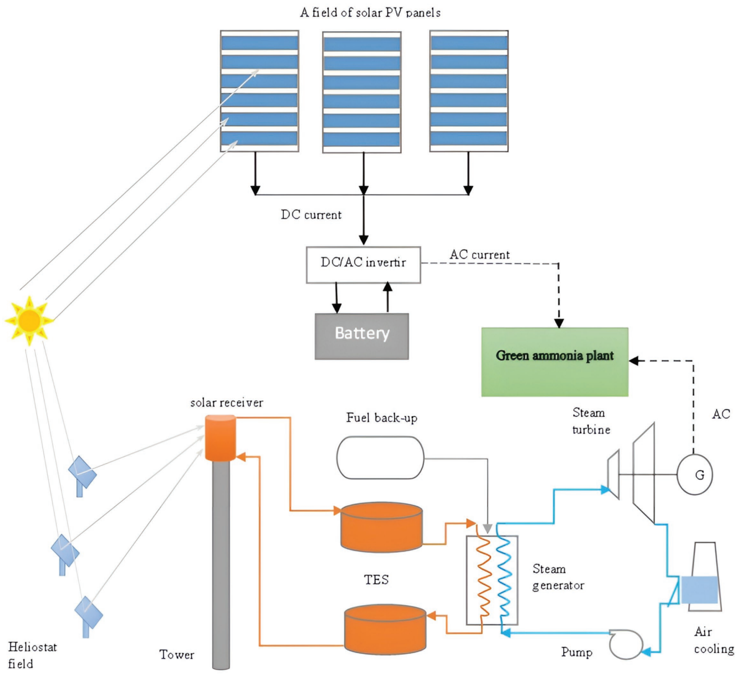

FIGURE 26.2 Hybrid solar power plant used to power the green ammonia production chain. AC: Alternative current, DC: Direct current, G: electric generator. TES: Thermal energy storage. Orange: Heat transfer fluid loop. Blue: Water/steam cycle.

Source: Authors.

field, a solar receiver, thermal energy storage, and a power block. The heliostat field collects solar rays and focuses them on the solar receiver. The solar receiver then absorbs the solar rays, converts them into heat, and transfers this heat to a heat transfer fluid. The heat transfer fluid (orange) is then used to generate steam to operate the steam Rankine cycle to produce electricity. The PV unit mainly consists of PV panels, electric battery storage, and a DC/AC inverter.

Both thermal energy and electric battery storage are used in solar power plants. The hybridization of solar power with other renewable energy sources is also feasible. One of the most promising configurations is hybrid solar PV and wind, which offers a high capacity factor and a low levelized cost of electricity (LCOE).

Energy consumption and costs

The Haber–Bosch process is well developed and optimized. It requires 0.6 kWh/kg of NH_3, which also includes the power demand to compress the hydrogen and nitrogen input into the reactor pressure at 150 bar (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018). The ASU requires 0.119 kWh/kg of nitrogen to produce the required nitrogen from the air (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018). Finally, the electrolysis process is the most energy-consuming process, requiring 53.40 kWh/kg of hydrogen (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018). As the further analyses of these processes in the last section of this chapter show, the power requirement of the electrolyzer represents more than 93% of the total power requirement of a green ammonia plant.

In addition, electrolysis requires approximately 9 liters of water to produce 1 kg of hydrogen. As freshwater access can be an issue in water-stressed areas such as Saudi Arabia, seawater could be used as an alternative in coastal areas. Using mechanical vapor compression for desalination requires an electricity demand of 22.75 kWh/m^3 of water and an installed CAPEX of \$5.72/m^3 per year (Morgan 2013). Using reverse osmosis for desalination requires an electricity demand of 3–4 kWh/m^3 of water and costs approximately \$0.7–2.5 per m^3 of water (IEA 2019). This has only a minor impact on the total cost of water electrolysis, increasing hydrogen production costs by just \$0.01–0.02/kg of hydrogen (IEA 2019).

The CAPEX of the electrolyzer, ASU, and Haber–Bosch process can be calculated using the factorial method in Equation (1) (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018):

$$CAPEX = KS^n \tag{1}$$

where K is the cost constant and S is the characteristic size parameter, which is specific to a given type of process.

Table 26.1 lists the values of the cost constants and index (n) used for each process.

The analysis presented in the last section of this chapter shows that the CAPEX amounts of the electrolyzer and Haber–Bosch process represent 76% and 19% of

TABLE 26.1 Indices and characteristic sizes used to calculate the CAPEX of each process (currency: USD)

Process	*K*	*S*	*n*
Haber–Bosch	4.42E6	Mean tonne per day of NH_3 produced	0.5
ASU	5.1E6	Mean tonne per day of nitrogen produced	0.49
Electrolysis	1143	Rated power (kW)	1

Source: Nayak-Luke, Banares-Alcantara, and Wilkinson (2018).

Note: K is the cost constant, *S* is the characteristic size parameter, and *n* is an index.

the total CAPEX of a green ammonia plant, respectively. To reduce the costs of the electrolyzer, some companies such as Thyssenkrupp AG are offering electrolyzers in prefabricated skid-mounted modules to simplify construction (Thyssenkrupp 2021). The units are easy to transport and install and can be combined to realize projects of several hundred megawatts or gigawatts (Thyssenkrupp 2021). In addition, some companies such as De Nora are working to develop more efficient electrolysis cells that raise system efficiencies above 80% (Thyssenkrupp 2021). The lifetime of commercial electrolyzers is approximately 30 years. This is with 98% availability and high operational flexibility (variation in load changes between 10% and 100% in less than 30 seconds; Thyssenkrupp 2021), which allows them to adapt to fluctuations in solar energy resources.

The cost of solar electricity in areas with abundant solar resources has dramatically decreased over the past decade. During 2010–2019, PV costs declined by 82% and CSP costs by 47% (IRENA 2021). Utility-scale solar PV can produce power for less than the cheapest new fossil fuel-fired power plant (IRENA 2021). Moreover, the number of PV projects with very low electricity costs (i.e., below \$0.02/kWh) is increasing. Indeed, the period from January 2020 to April 2021 saw three record low bids for solar PV, starting with \$0.0157/kWh in Qatar. This was followed by \$0.0135/kWh in the UAE and \$0.0104/kWh in Saudi Arabia (IRENA 2021). In addition, Saudi Arabia awarded Électricité de France S.A. and Masdar the contract for the 400 MW Dumat al Jandal wind farm at a price of \$0.0199/kWh (Global Petrol Prices 2021). The price of electricity in Saudi Arabia is \$0.048/kWh for households and \$0.069/kWh for businesses (Power Saudi Arabia 2019).

Saudi Arabia has the potential to produce more than 200 GW of power from onshore wind (ACWA Power 2018). Some parts in Saudi Arabia, including Aqaba, Jahid, Taif, and Yadamah, have high wind speeds (average wind speed in the cited areas is 7.4 m/s). They also have promising capacity factors (average capacity factor of 35.2%), making wind energy projects profitable (ACWA Power 2018).

The CAPEX and operation and maintenance costs of PV and CSP vary internationally by location. In Saudi Arabia, the CAPEX of PV is \$1008/kWh, whereas it is \$596/kWh and \$651/kWh in India and China, respectively (IRENA 2021). The global-weighted average installed cost of PV in 2020 was \$883/kWh (IRENA 2021). The O&M costs of the parabolic trough and solar tower in Saudi Arabia are \$0.012/kWh and \$0.011 USD/kWh, respectively (IRENA 2021). The capacity factor of CSP plants increased from 30% to 42% between 2010 and 2020 (IRENA 2021). It is expected that the LCOE of CSP plants would be approximately \$0.076/kWh for CSP projects commissioned worldwide in 2021 (IRENA 2021). In September 2021, a record low of \$0.03399/kWh was announced for CSP technology in the 380 MW Likana CSP project in Chile (PV Magazine 2021). In 2020, the average installed cost of CSP plants in the 150 MW size range was \$4581/kW (IRENA 2021).

Carbon dioxide (CO_2) gas emissions

Fossil fuels (mainly natural gas) are the primary feedstock for the hydrogen used to produce ammonia. As a result, ammonia production in 2018 generated approximately 500 million tonnes of CO_2, which represents approximately 1.8% of global CO_2 emissions (The Royal Society 2020). Hydrogen production accounts for approximately 90% of the CO_2 emission in the synthesis of ammonia. Thus, reducing the CO_2 produced during the manufacturing process depends primarily on the hydrogen source (The Royal Society 2020). Steam methane reforming is the most widely used technique for producing hydrogen from natural gas. However, it is carbon-intensive and produces 9–10 kg of CO_2 per kg of hydrogen when natural gas is used as both a feedstock and a fuel.

An ammonia plant that uses renewable electricity to produce hydrogen, while using fossil fuel-based electricity to produce nitrogen and compress nitrogen and hydrogen for the Haber–Bosch process, has cradle-to-gate greenhouse gas (GHG) emissions 91% lower than that of an unabated ammonia plant. Specifically, an unabated ammonia plant produces 2.55 metric tonnes of GHG emissions for each tonne of ammonia, while a green ammonia plant produces 0.22 metric tonnes (Liu, Elgowainy, and Wang 2020).

Ammonia transport

Ammonia is a more efficient energy carrier than hydrogen when transported through ships, tanker trucks, and pipelines. High pressures are involved in transporting hydrogen gas. This limits the carrying capacity of a semi-tractor trailer to 340 kg of hydrogen (41 gigajoules [GJ]), whereas it can carry 26,600 kg of ammonia (500 GJ) (Bartels 2008). Ammonia is transported in commercial pipelines in the United States over a distance of 1,610 km at \$0.0344/kg of NH3 (\$0.194/kg of hydrogen). Estimates have shown that ammonia is nearly three times cheaper to transport in pipelines than hydrogen (Bartels 2008).

The ships used to transport ammonia are comparable to those used to transport liquid propane gas (Salmon, Banares-Alcantara, and Nayak-Luke 2021). Chartering ships is the most common method for the international transport of ammonia. However, the chartering rates of maritime vessels are highly volatile; in 2020, for instance, LNG charters for 160,000 m^3 ships ranged from $20,000/day to $120,000/day (Salmon, Banares-Alcantara, and Nayak-Luke 2021).

The contribution of transport to the levelized cost of ammonia (LCOA) is small; marine transport costs $0.5/ton/100 km (Hansson et al. 2020). The cost of transporting ammonia from the Dhiba port in northwestern Saudi Arabia to the Bremerhaven port in Germany (distance of 8,388 km) is $42/tonne. Ammonia has been proposed as a potential marine fuel that does not emit CO_2 from ships because it is a carbon-free molecule (Hansson et al. 2020). However, the risk of nitrogen oxides (NOx) and ammonia emissions must be managed. This is since tests show that the NOx emissions of ammonia-powered engines are 1,500–1,700 particles per million (ppm), while ammonia emissions are 1,600–2,500 ppm (Hansson, Fridell, and Brynolf 2020).

When a ship uses fossil fuels for propulsion, it releases approximately 2.28 kg of CO_2 per MWh of hydrogen transported for 1,000 km (Ishimoto et al. 2020). Thus, if the ship were to use fossil fuels, the transport of ammonia from the Dhiba port to the Bremerhaven port would release 19.12 kg of CO_2 per MWh of hydrogen transported (equivalent to 0.64 kg of CO_2 per kg of hydrogen).

Ammonia cracking

Ammonia cracking is the process of dissociating gaseous anhydrous ammonia into a mixture of gases. The resulting gas mixture is composed of hydrogen and nitrogen in the ratio 3:1, with a very small amount (20–100 ppm) of residual undissociated ammonia (SubsTech 2021). The gas can be further purified using molecular sieves, which reduces the ammonia content to 1–3 ppm (SubsTech 2021). Figure 26.3 shows the principal flow scheme of ammonia cracking.

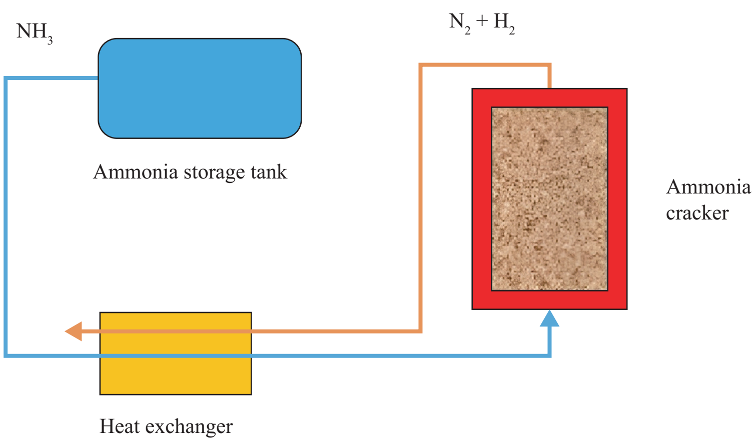

FIGURE 26.3 Ammonia cracking process.

Source: Authors.

In brief, ammonia is first preheated and then passed through a catalyst bed where it is cracked.

Metal catalysts with various supports are typically used to increase the reaction rate of ammonia cracking at reduced temperatures. Many studies have investigated ammonia cracking using different catalysts/supports in laboratory-scale reactors (Dilshani, Wijayananda, and Rathnayake 2022). Alumina (Al2O3) is the most studied support for ammonia cracking and (ruthenium) Ru catalysts are the most active compared with other metal catalysts over the Al2O3 support (Dilshani, Wijayananda, and Rathnayake 2022). Nevertheless, the high cost of Ru catalysts has led many researchers to focus on (nickel) Ni as an alternative catalyst for economical ammonia cracking. Therefore, Ru/Al2O3 and Ni/Al2O3 are the most developed catalyst/support options for ammonia cracking. However, a nickel-containing catalyst has been found to have a low cost and high technological maturity (Cesaro et al. 2021). The net energy required for ammonia cracking ranges from 0.28 to 0.30 MWh per tonne of ammonia (Giddey et al. 2017), representing 5.4%–5.7% of the energy in the fuel (energy content of ammonia is 18.8 MJ/kg).

The technology for ammonia cracking is commercially available at a small scale (i.e., less than 100 kg of hydrogen per hour of output; Cesaro et al. 2021). Small-scale ammonia crackers are commonly used in the mining and metallurgical industry (Ishimoto et al. 2020). In addition, a large-scale ammonia cracker has been designed (Ishimoto et al. 2020). For example, ammonia cracking based on Uhde® technology has an overall hydrogen recovery of 78% (with 1 kg of NH_3 and 0.13 kg of hydrogen as the final product; Cesaro et al. 2021).

The installed CAPEX of ammonia crackers can be calculated using the following formula (Wan et al. 2021):

$$CAPEX = 10.171X^{0.7451} \tag{2}$$

where CAPEX is in millions of US dollars and *X* represents the capacity of the cracker in tonnes of hydrogen per hour. Green ammonia is assumed to be exported from Saudi Arabia to Germany.

Grid electricity is a major source of CO_2 emissions in cracking and purification processes (Ishimoto et al. 2020). When the electricity is produced from fossil fuels, the cracking and purification of ammonia release about 35 kg of CO_2 for each megawatthour of hydrogen produced (equivalent to 1.18 kg of CO_2 per kg of hydrogen, assuming that 1 kg of hydrogen contains 33.6 kWh; Ishimoto et al. 2020).

High-temperature solar thermal energy can be used to crack ammonia. Both the central receiver and the solar dish can reach the required temperature for the ammonia cracking process. Figure 26.4 shows a potential design for the solar ammonia cracking process using central receiver technology. Liquid ammonia (green) is pumped from a storage tank through a heat exchanger to capture the waste heat from the hot gases exiting the cracking reactor. The preheated ammonia gas then passes through the solar receiver where it is heated to the temperature required by the cracking process. The solar receiver and cracker can be separated or combined

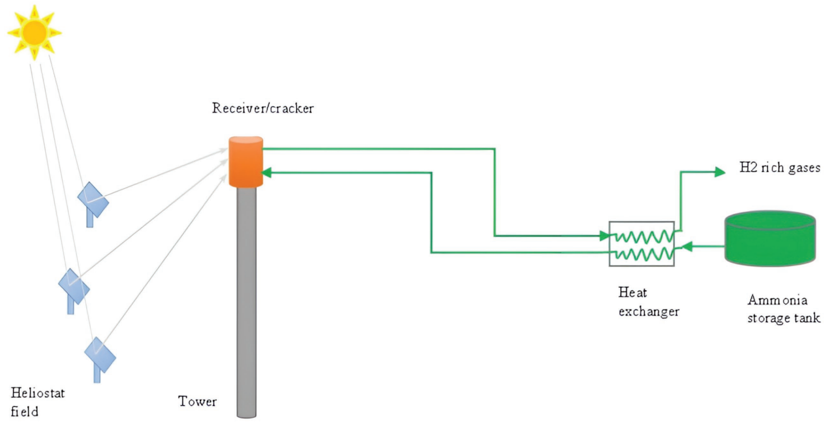

FIGURE 26.4 Solar ammonia cracking process with the direct heating of ammonia in the receiver.

Source: Authors.

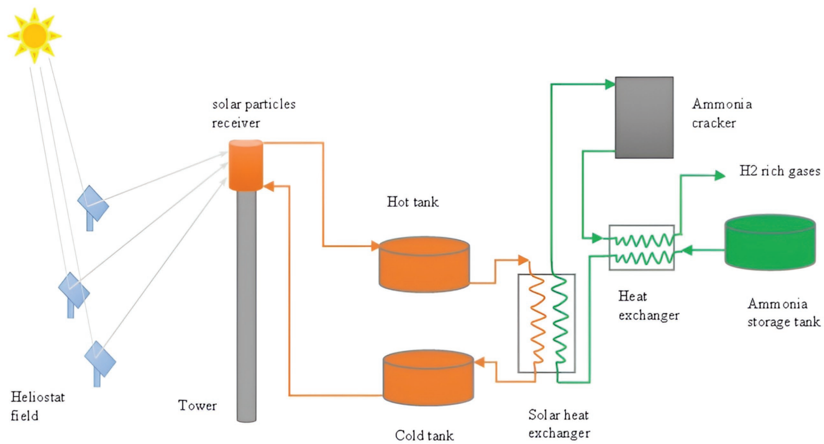

FIGURE 26.5 Solar ammonia process using solar particle receiver technology (indirect heating of ammonia).

Source: Authors.

in a single unit. Figure 26.4 shows the solar thermal cracking process with central receiver technology and a combined receiver/cracker.

The use of particles as a heat-transfer medium allows for thermal energy storage. As shown in Figure 26.5, ammonia gas is heated indirectly using a particle heat exchanger. The particles can be stored and their thermal energy recovered when required. The particle heat exchanger can be separated from the cracker or combined in a single unit. Figure 26.6 shows the case of a separated heat exchanger and cracker.

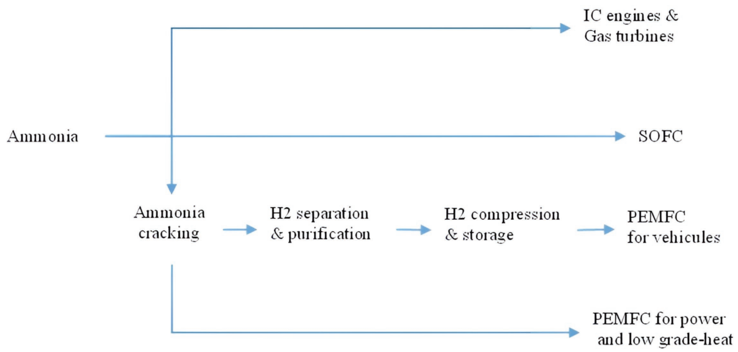

FIGURE 26.6 Utilization of ammonia as a fuel.

Source: Authors.

The use of high-temperature solar thermal energy to crack ammonia saves up to 22% of the produced hydrogen compared with a cracking process that uses hydrogen as the fuel. The capacity factor of a solar thermal cracking process without thermal energy storage ranges from 25% to 40% depending on the annual solar irradiation (in Germany, the capacity factor should be approximately 25%). Thus, fuel savings of up to 40% can be achieved using a solar cracking process without thermal energy storage. When solar thermal energy storage is integrated into the solar thermal cracking process, fuel savings can reach 100%. Further, using solar thermal energy to crack ammonia can avoid up to 1.18 kg of CO_2 emissions per kg of hydrogen produced.

Utilization of ammonia

Figure 26.6 highlights the various applications of ammonia, including its directly use in gas turbines, internal combustion engines, and electrochemical devices. This process involves the delivery and storage of ammonia as the fuel for power generation. For use as a vehicle fuel, ammonia must be cracked to form hydrogen before vehicle filling. The level of trace ammonia in the hydrogen stream must be reduced to meet fuel purity requirements (e.g., <0.1 ppm NH_3) for proton-exchange membrane fuel cells (PEMFCs; U.S. Department of Energy 2015) Pure hydrogen is cooled and compressed to a pressure above the storage pressure (880 bar), allowing the rapid filling of the hydrogen tanks (Rte 2021). This process is normally carried out at a refueling station and may require up to 6.4 kWh (19.2% of hydrogen lower heating value) of energy per kilogram of dispensed hydrogen (Giddey et al. 2017, Rte 2021).

For PEMFC-based transport, the net conversion efficiency ranges from 11% to 19%. When ammonia is used for stationary applications in fuel cells, the net-combined heat and power efficiency ranges from 25% to 39%. Hydrogen from the ammonia cracker is used directly without any need for compression (Giddey et al. 2017).

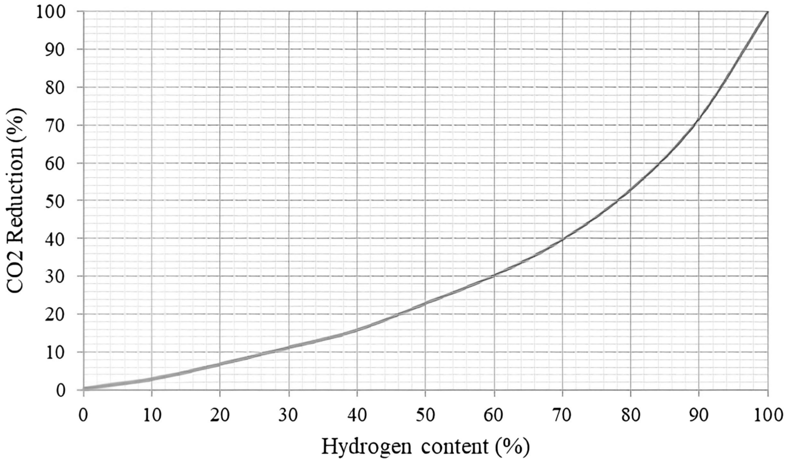

FIGURE 26.7 CO_2 reduction as a function of the hydrogen content in the fuel mix of a gas turbine.

Source: Adapted from Goldmeer, Catillaz, and Donohue (2021).

The overall efficiency of ammonia combustion in an internal combustion engine can vary from 15% to 21%. This efficiency ranges from 24% to 31% in a combined-cycle gas turbine (Giddey et al. 2017).

Assuming that green ammonia is cracked in Germany and used to power gas turbines, Figure 26.7 shows the CO_2 emissions cut as a function of hydrogen/methane blends. For example, the Siemens SGT-800, a medium (62.5 MW) turbine, can run on 50% hydrogen. When this turbine is powered with 50% hydrogen as the fuel, CO_2 emissions reduce by 23%. The CO_2 emissions of fossil fuel-driven gas turbine power plants are 486 tonnes of CO_2-equivalent per MWh (Goldmeer, Catillaz, and Donohue 2021). Thus, a gas turbine blended with 50% hydrogen releases 374.22 tonnes of CO_2-equivalent per MWh, which is a 23% reduction.

Case study: cost of the Neom project for the production and export of green ammonia

In 2020, Air Products, in conjunction with ACWA Power and Neom, announced the signing of an agreement for a green hydrogen-based ammonia production facility powered by renewable energy. The project, which will be owned by the three partners equally, will be located in Neom in northwest Saudi Arabia. The project will produce 1.2 million tonnes of green ammonia per year at full scale for export to the global market.

Hydrogen, nitrogen, and pure water are required to produce ammonia. Their flow rates can be determined from the stoichiometry of ammonia. The molecular mass of ammonia is 17.03 g/mole of which nitrogen is approximately 14 g/

mol. Thus, ammonia is 82.2% nitrogen by mass and 17.8% hydrogen by mass. A 1.2 million tonnes per year (3,287.67 tonnes per day) ammonia plant would therefore require 2703 tonnes of nitrogen and 585 tonnes of hydrogen per day. A large amount of pure water feed is also necessary for electrolyzers to produce hydrogen. To produce one mole of ammonia gas, pure water (1.5 mole) is required. An ammonia plant that can reach 3,288 tonnes per day would thus require approximately 5,212 tonnes of distilled water per day. Table 26.2 summarizes the mass flow rates of nitrogen, hydrogen, and pure water.

It is important to determine the power requirements to estimate the required size of an electric power plant. The specific energy consumption for the production of hydrogen is 53.4 kWh/kg, 0.119 kWh/kg for nitrogen, and 0.600 kWh/ kg for ammonia (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018). Distillation requires an additional 0.02275 kWh/kg (Morgan 2013). Table 26.2 also presents the power required for each process and Figure 26.8 shows the power share.

TABLE 26.2 Nominal mass flow rates for the production of 1.2 million tonnes ammonia per year

Product	*Process*	*Amount (tonnes/day)*	*Required power (MW)*
Ammonia	Ammonia synthesis	3,287.67	82.19
Nitrogen	Air separation	2,702.72	13.40
Hydrogen	Electrolysis	584.95	1,301.51
Water	Desalination	5,212.40	4.94

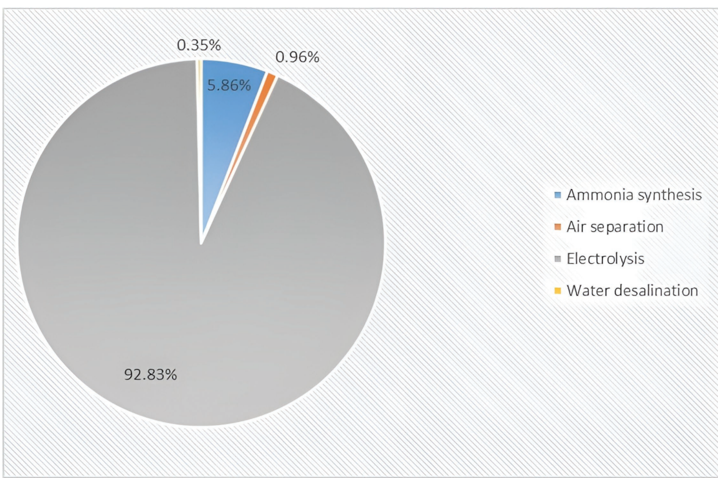

FIGURE 26.8 Power share of each process of the green ammonia plant.

Source: Authors.

Figure 26.8 shows that the power requirements are dominated by water electrolysis. For a 1.2 million tonne per year plant, the total power requirement is 1,402 MW, with 1,301 MW needed for electrolysis, representing 93.8% of the total. The synthesis loop requires 82 MW of power or approximately 5.7% of the total power requirement. The ASU and water desalination are not power-intensive processes and together comprise only 1.31% of the power required; the ASU requires 13.40 MW, whereas water desalination requires 5 kW.

The installed CAPEX is almost entirely for the electrolyzer and Haber–Bosch process. For the Neom green ammonia plant, the total calculated CAPEX (using the data given in the third section) is $1,313 million, with $1,002 million required for the electrolyzer, accounting for 76.3% of the total CAPEX. The synthesis loop requires $253 million, or approximately 19.3% of the total CAPEX. The CAPEX of the ASU is $57.40 million. The CAPEX of the water desalination process accounts for only 0.06% ($0.75 million). Table 26.3 highlights the CAPEX of the Neom green ammonia plant. The annual OPEX (without electricity) is assumed to be 5% of the CAPEX (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018). The total OPEX of the Neom green ammonia plant is thus $66 million per year.

The electricity price depends on the solar power technology. Table 26.4 presents the LCOE and annual capacity factor of four solar power technologies. (The storage system is not considered for PV and CSP.) For hybrid PV-wind, the size of the electric storage system is assumed to be sufficient to store electric energy from wind turbines during the day. For hybrid PV-CSP, the PV panels produce electric energy during the day, whereas CSP stores solar thermal energy to be used at night or when the electric energy from the PV panels is insufficient.

TABLE 26.3 CAPEX of the Neom green ammonia plant

Process	*CAPEX (million USD)*	*Proportion (%)*
Ammonia synthesis	253	19.3
Air separation	57.40	4.37
Electrolysis	1,002	76.3
Desalination	0.75	0.06

TABLE 26.4 LCOE and capacity factor of four solar power technologies

Solar power technology	*LCOE (USD/kWh)*	*Capacity factor (%)*
Solar PV	0.0104	20
CSP	0.076	42
Hybrid PV-CSP	0.055	62
Hybrid PV-wind	0.029	55.2

Source: IRENA (2021).

The LCOA produced by the Neom project can be calculated using the following formula (Nayak-Luke, Banares-Alcantara, and Wilkinson 2018):

$$LCOA = \left(\frac{CAPEX + OPEX + E}{ammonia \;\; production} \right)$$

where E is the cost of electricity. The discount rate is not considered in the calculation.

Table 26.5 lists the LCOA and levelized cost of hydrogen (LCOH) produced by the Neom plant for each solar power technology. The lifetime of the plant is 25 years and the number of operating hours corresponds to the capacity factor of the solar power technology. The table shows that solar PV-wind provides the lowest LCOA and LCOH, namely, $714/tonnes and $33.57/kg, respectively.

As mentioned above, the cost of transporting green ammonia from Saudi Arabia to Germany is $42/tonne. Therefore, the annual transport cost of ammonia produced by the Neom project is $50.4 million. When ammonia reaches German ports, it is cracked to produce hydrogen. The hydrogen recovery rate of the cracker is 78% (Cesaro et al. 2021). The cracker is specifically designed to crack the ammonia produced by Neom and has a daily production capacity of 456 tonnes of hydrogen. Considering the energy consumption of the cracker at 300 kWh/tonnes of ammonia, its capacity must have a capacity of 41.1 MW_{th}. The CAPEX of the cracker is $163.3 million (estimated using Equation (2)). Assuming an annual OPEX of 5% of the CAPEX and a lifetime of 25 years, Table 26.6 provides the LCOH produced by the cracker. It shows that the LCOH for an ammonia plant powered by CSP is

TABLE 26.5 LCOA and LCOH of the Neom project for each solar power technology

Solar power technology	*LCOA (USD/tonne)*	*LCOH (USD/kg)*
Solar PV	1,023	4.89
CSP	2,080	10.67
Hybrid PV-CSP	1,064	5.42
Hybrid PV-wind	714	3.57

TABLE 26.6 LCOH produced by cracking ammonia

Origin of ammonia	*LCOH (USD/kg)*
Plant powered by solar PV	7.76
Plant powered by CSP	15.38
Plant powered by hybrid PV-CSP	8.06
Plant powered by hybrid PV-wind	5.54

far higher than that in the three other cases ($15.38/kg compared with $7.76/kg for a plant powered by PV, $8.06/kg for a plant powered by hybrid PV-CSP, and $5.54/kg for a plant powered by PV-wind).

The LCOH for the three cited cases is comparable to the findings of previous studies. Nasharuddin et al. (2019) evaluated the cost of producing hydrogen from green ammonia using both centralized and decentralized case scenarios. The LCOH was estimated at $5.50/kg. In another techno-economic analysis, Lee et al. (2019) reported the results of a validated first-law thermodynamic model of a 30 Nm^3/h hydrogen plant produced from ammonia. The LCOH was evaluated at Euro 5.32/kg of hydrogen. Makhloufi and Kezibri (2021) carried out a techno-economic analysis of the large-scale cracking of green ammonia for hydrogen production and estimated the LCOH to be Euro 5.65/kg of hydrogen.

In 2021, the price of 1 kg of hydrogen at all public hydrogen mobility filling stations in Germany was Euro 9.50 (approximately $11.12; H2 2021). This means that producing green ammonia in Saudi Arabia (using solar PV, hybrid PV-CSP, or hybrid PV-wind) and exporting it to Germany for use in refueling stations might be economically feasible. Of the three systems, hybrid PV-wind provides the cheapest hydrogen produced from cracking green ammonia (LCOH = $5.54/kg).

The CO_2 emissions of the green ammonia plant at Neom are 0.264 million tonnes per year. By contrast, the CO_2 emissions of gray ammonia of a similar size (that uses natural gas as the feedstock) are 3 million tonnes per year. Thus, the annual CO_2 emission cut is 2.736 million tonnes or a 91.2% reduction. During its lifetime, the Neom green ammonia plant thus avoids the emission of 66 million tonnes of CO_2.

The CO_2 emissions from transporting the ammonia produced by the Neom plant are 136,704 tonnes per year if fossil fuel-powered ships are used. If ships use ammonia as fuel, CO_2 emissions can be avoided. Assuming that electricity from fossil fuels is used for ammonia cracking and purification in Germany, 1.2 million tonnes of ammonia produced by the Neom plant would release an estimated 1.1 million tonnes of CO_2 per year (Table 26.7). These emissions could be avoided by using hydrogen as the fuel to crack ammonia.

If the hydrogen produced by ammonia cracking is used to feed Siemens gas turbines (50% hydrogen, 50% methane), the total annual hydrogen production from cracking the ammonia produced by Neom would be 936,000 tonnes. This is equivalent to 28,022.4 GWh_{th} (1 kg of hydrogen = 33.6 kWh). The conversion of this amount of energy into electricity with 38% gas turbine efficiency would provide

TABLE 26.7 CO_2 avoidance from the production, transport, cracking, and use of NEOM ammonia per year

Process	*Production*	*Transport*	*Cracking*	*Use*
Amount (tonnes)	2.736 million	136,704	1.1 million	1.336 million

10,649 GWh_e. The amount of CO_2 avoided owing to the use of hydrogen in gas turbine power plants would be 1,336 million tonnes of CO_2 per year.

The use of a high-temperature solar thermal process to crack the ammonia produced by the Neom project would allow savings of up to 36,638 kg of the produced hydrogen every year. For a solar thermal cracking process installed in Germany without thermal energy storage (approximate capacity factor of 25%), the avoided CO_2 emissions would be 10.81 tonnes every year. The integration of a thermal energy storage unit into the solar thermal cracking process would avoid up to 118.5 kg of CO_2 per day.

Conclusion

Green hydrogen is considered to be a highly promising vector for the deep decarbonization of the energy system and hard-to-abate industrial sector. To secure access to this resource, Japan, Germany, and South Korea have announced plans to import hydrogen. Other major energy-consuming countries are likely to follow. Saudi Arabia's vast solar and wind resources allow it to produce and export green hydrogen. Ammonia, a promising hydrogen derivative, can enable the transport of hydrogen by enhancing its energy density at a relatively low cost using mature technologies. The techno-economic analysis showed that the lowest cost of green ammonia in Saudi Arabia is $714/tonnes if solar PV and wind are used to power the green ammonia plant. The lowest cost of the hydrogen produced from ammonia cracking is $5.54/kg. During its lifetime, the Neom green ammonia plant will avoid 66 million tonnes of CO_2 emissions. Further, using solar energy or renewable hydrogen to crack the ammonia would avoid 1.1 million tonnes of CO_2 emissions per year. Cracking ammonia using solar thermal technologies is an attractive option, but a relatively new idea that requires more effort to reach a commercial level.

Overall, much research and development is required to make producing and cracking green ammonia competitive with that of brown or gray ammonia. Reducing the CAPEX and energy consumption of the electrolyzer could reduce the LCOA significantly. Further, developing more efficient crackers would increase hydrogen recovery and therefore reduce the final cost. Finally, if Saudi Arabia is aiming to export green ammonia, local production technologies must be improved. In addition, cracking technologies could be developed in collaboration with other ammonia-importing countries.

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27

DESALINATION

Water supply for Saudi Arabia's green hydrogen production

Friedrich Alt and Christopher M. Fellows

Desalination and hydrogen

Seawater desalination has been for decades an important source for the Kingdom's water supply. When considering to produce "green hydrogen" in the future in large quantities in the Kingdom, it would be desirable to receive the water required for the electrolysis process also from a "green desalination" plant. This would be technically feasible if a dedicated desalination plant would be built together with the hydrogen production facility. However, economic aspects may lead to the use of desalinated water from the water distribution system or from a co-located existing seawater desalination plant. Since a significant capital investment will be required in the desalination industry, to reduce the CO_2 emission, we may see in a transition period until 2050 or partly beyond desalination plants still operating with a certain allocated amount of CO_2 emission.

When looking into the current seawater desalination industry, a key question is, what to do with thermal desalination plants for which the energy consumption and allocated CO_2 emission is on average about five times higher than seawater reverse osmosis (SWRO) plants. While a large number of older thermal desalination plants including the world largest plant, Jubail 2, with a capacity of 948,000 m^3/day will be decommissioned in the near future, those desalination capacities will be replaced by the more energy-efficient SWRO technology.

However, there are large capacity thermal desalination plants like Ras Al Khair with about 720,000 m^3/day capacity and Yanbu 3 with 550,000 m^3/day capacity which have been built during the past 10 years. Those plants will be most likely kept in operation for a longer period of time, whereby one economic aspect hereby is that those plants are coupled with power generation plants so that the desalination plant cannot be easily replaced without losing major power generation

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capacities or requiring significant capital investments to modify the power plants. Also it should be kept in mind that under the current goal of the National Renewable Energy Program (NREP), only 50% of the total power grid energy would be produced by renewable energy so that fossil fuel-driven power plants would be also still required (National Renewable Energy Program 2022).

Furthermore, when looking at the green hydrogen production, a high purity distillate as can be produced by thermal desalination plants may have an advantage over a drinking water produced by SWRO plants, since the water quality is influencing the water demand, energy consumption, and efficiency of a green hydrogen production plant. The water consumption for the hydrogen production may be limited to about 10 kg of high purity distillate per kg of hydrogen, while it may be up to 50% higher when using a drinking water quality as produced by SWRO plants or a typical tap water. A drinking water would require additional pretreatment upstream of the hydrogen production which has to be considered as well, when considering overall power consumption and capital cost for a hydrogen production system.

While land availability for large capacity wind parks will play also a role for the selection of a suitable location for a green hydrogen production facility, it could be for economical reasons of advantage when co-locating large hydrogen production close to a thermal desalination plant like the Ras Al Khair multistage flash (MSF) desalination plant which could deliver a high purity distillate. Of course, considering that thermal desalination plants like Ras Al Khair may be also decommissioned latest in about 20–30 years from now, the water supply from those plants would be a solution for a transitional period toward 2050, which may give also time to replace the water source for a hydrogen plant by a better technology than available now.

Minimizing CO_2 emissions during seawater desalination

Zero liquid discharge (ZLD) technology, which can be theoretically used for the production of desalinated water as well, is not described here, since it is considered that it could be applied economically only if the produced salt could also be used. Due to the limited demand of salt, the ZLD technology could be applied only to a small fraction of the required total desalination plant capacities for the Kingdom.

Desalination technology

Thermal desalination – energy consumption and allocated CO_2 emissions

The thermal desalination technology has been applied for drinking water production since the 1960s. At this time, R&D made big efforts toward high energy efficiencies, for example, an MSF desalination plant, shown in Figure 27.1, built in 1968 in California, USA (United States Department of the Interior 1971). This plant had

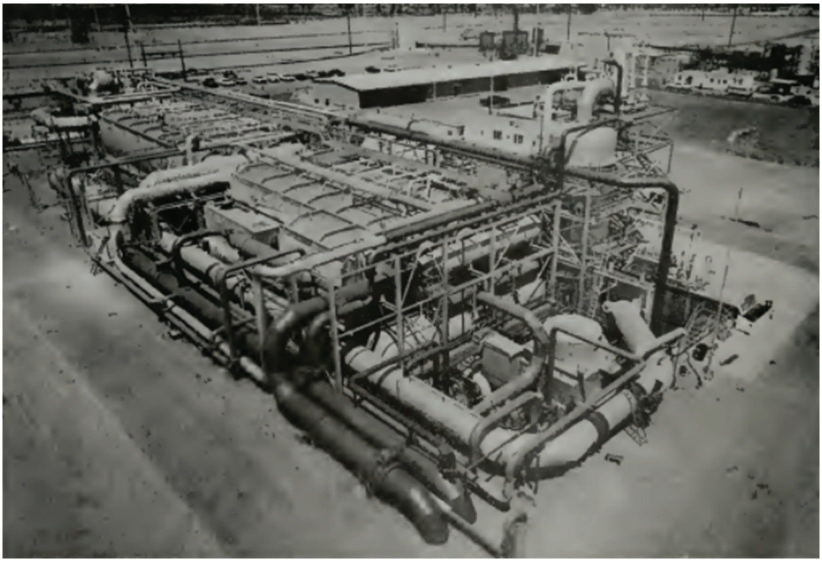

FIGURE 27.1 MSF desalination plant built in the 1960s.

Source: United States Department of the Interior (1971).

a capacity of approximately 3,800 m^3/day and a performance ratio (PR) of about 20 kg/2,326 kJ.

The PR, which is a commonly used measurement of kg mass of distillate produced per 2,326 kJ of net steam energy consumed as heating steam, has been for this plant about double the PR's of most commercial thermal desalination plants currently in operation in the Middle East region. This means theoretically, if applying a more than 60-year-old plant concept, the steam energy consumption of thermal desalination plants could be cut substantially in half. While a thermal desalination system is consuming the thermal energy described with the PR, it is consuming in addition also electrical energy, commonly described as auxiliary power consumption.

To allow a comparison of the total energy consumption of thermal desalination systems to the energy consumption of other systems like SWRO plants, the thermal energy consumption is converted into a convertible steam energy. Hereto the steam condition at the point of source in the power plant has to be known. In some cases, steam may be supplied from the discharge of a backpressure turbine as illustrated in Figure 27.2 (left), while in other cases, steam may be extracted from a condensing steam turbine (Figure 27.2 (right)).

Knowing the steam supply condition and the actual steam discharge condition at the turbine condenser, the convertible steam energy of the steam supplied to the desalination plant can be calculated. In case of a backpressure turbine where no

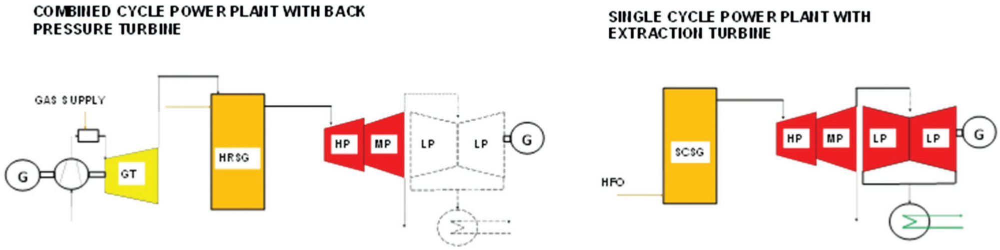

FIGURE 27.2 Steam supply from a backpressure turbine or condensing steam turbine.

Source: Author.

turbine condenser exists, a fair assumption of steam condition at a reference turbine condenser has to be made, to calculate the convertible steam energy. With a common steam supply pressure from a backpressure turbine in the range of 2.5 bar and a common PR of a desalination plant in the range of 9–10 kg/2,326 kJ, the convertible steam energy consumption would be in the range of about 12–15 kWh/m^3, while this value can exceed 20 kWh/m^3, if higher steam pressure is used as it is common in case of steam extraction from condensing turbines.

The auxiliary power consumed with the process pumps may be typically in the range of 3–4 kWh/m^3 for the MSF desalination plants while it is in the range of about 2.0–2.5 kWh/m^3 for multi-effect desalination (MED) plants, which results in a total allocated energy consumption in the range of about 14–19 kWh/m^3 or above.

Next step is the allocation of CO_2 emission to the thermal desalination plant. Hereto, relevant factors are the power plant configuration and related heat rate and the type of fuel used for the power plant operation. Knowing those factors, the CO_2 emission per kWh generated power can be calculated. With a combined cycle power plant (CCPP) configuration and gas firing, the specific CO_2 emission may be typically in the order of 0.40 kg/kWh. With a high-efficiency Single Cycle Power Pant (SCPP) with heavy fuel oil (HFO) firing, the specific CO_2 emission may be about 0.60 kg/kWh, wherein this value will increase with lower power plant efficiency. With the above-described allocated energy consumption, those values are resulting in a specific allocated CO_2 emission of the thermal desalination plants in the range of 5.6–11.4 kg/m^3 or above. Under the assumption to use thermal desalination plants with maximum PR in the range of 20 kg/2,326 kJ in combination with gas-fired CCPP, the CO_2 emission could be theoretically reduced to a level of about 3–4 kg/m^3.

Distillate supply for hydrogen production from existing thermal desalination plants

Considering for the hydrogen production a low consumption of high purity distillate in the order of 10–12 kg distillate per kg of hydrogen the energy consumption allocatable to the hydrogen production would be in the range of 0.14–0.23 kWh per kg hydrogen. Considering that the energy consumption for the hydrogen electrolysis process is in the range of 40 kWh per kg of hydrogen, the allocated energy consumption from the thermal desalination plants would be in the order of 0.4%–0.6 % of the total energy consumption for the hydrogen production. The allocated CO_2 emission would be with existing thermal desalination plants in the order of 56.0–136.8 kg per ton of hydrogen. With a LHV (lower heating value) of the hydrogen of 33.3 kWh/kg this allocated CO_2 emission would be equal to 0.0017–0.0040 kg CO_2/kWh H_2 energy, which would be in comparison to a CO_2 emission allocated to one kWh of power generated in a CCPP, in the order of 0.4%–1.2%.

Seawater reverse osmosis

The spiral wound membranes as illustrated in Figure 27.3 have been described already in previously in 1970 as the state-of-the-art seawater desalination technology (Department of Water Resources 1969) and even more recently in Membrane Processes, Food Process Engineering and Technology, 2009.

This membrane type is still the base for the most efficient and reliable SWRO technology. While the energy consumption may have been originally above 6 kWh/m^3, it dropped over the years with the help of energy recovery systems to a current practical level in the range of 3.0 kWh/m^3, while older operating systems may still consume more than 4.0 kWh/m^3.

Considering the power supply by existing fossil fuel-driven SCPP or CCPP power plants, the specific allocated CO_2 emission for currently operating SWRO plants may be in the range between 1.2 and 2.4 kg/m^3 or above.

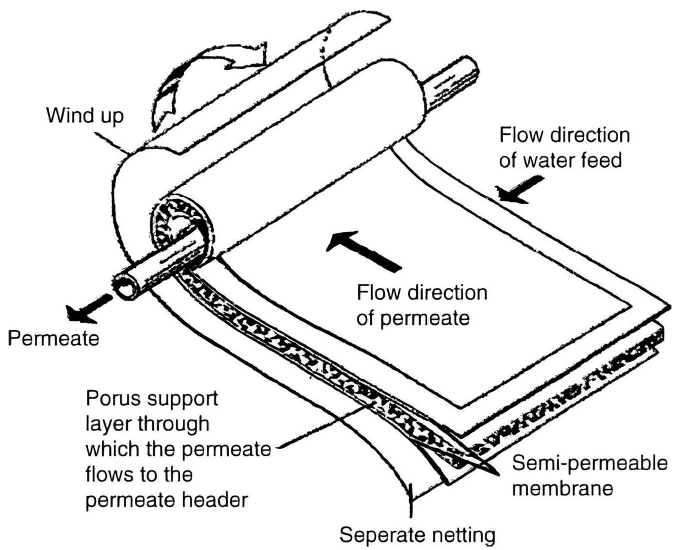

FIGURE 27.3 Spiral wound membrane, 2009.

Source: Food Process Engineering and Technology (2009).

Considering, that the energy consumption and allocated CO_2 emission is roughly by a factor 5 lower than for the existing thermal desalination plants, but the water demand for the hydrogen production would increase by a factor 1.2–1.5 with the SWRO permeate quality, the corresponding allocated CO_2 emission for the hydrogen production would be in the range of about 0.0004–0.0012 kg CO_2 per kWh H_2 energy.

Energy supply

National renewable energy program

Under the NREP, it is foreseen to supply by 2030 about 50% of the grid power by renewable energy, which includes the installation of a total solar photovoltaic (PV) capacity of 40 GW in combination with a total wind energy capacity of 16 GW (ArabNews 2021).

While those renewable power systems may primarily feed directly into the grid, existing conventional power plants, which are currently operating primarily at or near full load, will have to operate in future in a relatively wide load range to cover the total power demand in combination with the fluctuating renewable energy supply.

The NREP will tentatively reduce the CO_2 emission for SWRO desalination plants by about 50%, provided they are connected to the grid. If power is supplied to SWRO plants directly from co-located fossil fuel-driven power generation plants like the Ras Al Khair SWRO plant, such reduction of allocatable CO_2 emission would be not applicable.

Desalination directly coupled with renewable energy production

Small capacity desalination units may in future continue to operate with grid power but may be designed to allow a certain load variation to help limit the required load variations of the fossil fuel-fired power plants.

For the power supply of desalination plants, dedicated renewable energy generation systems may be considered to limit the direct use of grid power to a minimum. One example may be the Al Khafji SWRO desalination plant with a capacity of 60,000 m^3/day completed in 2016, which receives power from a 14 MW solar PV plant, sufficient to produce the total power consumption. Another example is the Yanbu 4 – SWRO plant with a capacity of 450,000 m^3/day in combination with a 20 MW PV plant which may cover about 25% of the energy consumption. This plant is scheduled to go into operation in 2025 (ArabNews 2021).

Besides the need to locate desalination plants on or near the coastline, a number of other factors must be considered. These factors include local solar energy and/or wind power density, land availability for solar PV plants, and wind power generation. Figure 27.4 An example of a general concept of a future SWRO plant operating primarily with renewable energy (Alt 2022). Hereto, the following engineering aspects may be considered.

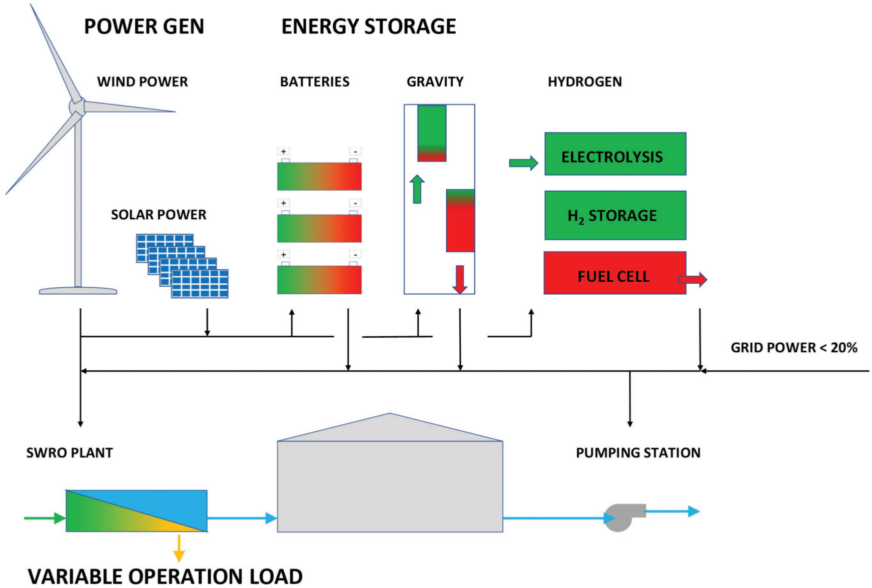

FIGURE 27.4 Example of a future SWRO plant primarily driven by renewable energy.

Source: Author.

The cost of solar PV power fed to the power grid is currently about 0.010 US$ per kWh (600 MW Al Shuaiba PV plant) (PV Magazine 2021), significantly lower than wind power with about 0.020 US$ per kWh (Dumat Al Jandal 400 MW windfarm) (Saudi Energy 2022)).

However, for the optimization of an off-grid renewable power supply system, required energy storage capacities and increased desalination plant design capacities to allow load variations and related capital cost have to be considered. Using wind power may be preferred if available, since the capacity factors[1] (CFs) for most current wind power generation plants are in the range of 0.40–0.45, which is almost double the CFs achievable with solar PV plants, so that the required energy buffering systems would be much smaller when using wind energy. Further, the wind power generation technology allows to go with current wind turbines to CFs up to a level of about 0.67 if high wind power densities above 1,000 W/m^2 are available like in the region of the Gulf of Aquabar, where NEOM city is located. Future developments of wind turbines could allow similar high CFs at lower wind power densities in the region of 400–600 W/m^2, as applicable for regions like Dumat Al Jandal where a first wind park went into operation in 2021 (Edie Newsroom 2021) or the Starah area, one potential site for a future wind park (NREP) or the Ras Al Khair Area, where one of Saudi Arabia's largest combined power & desalination plant is located (Figure 27.5).

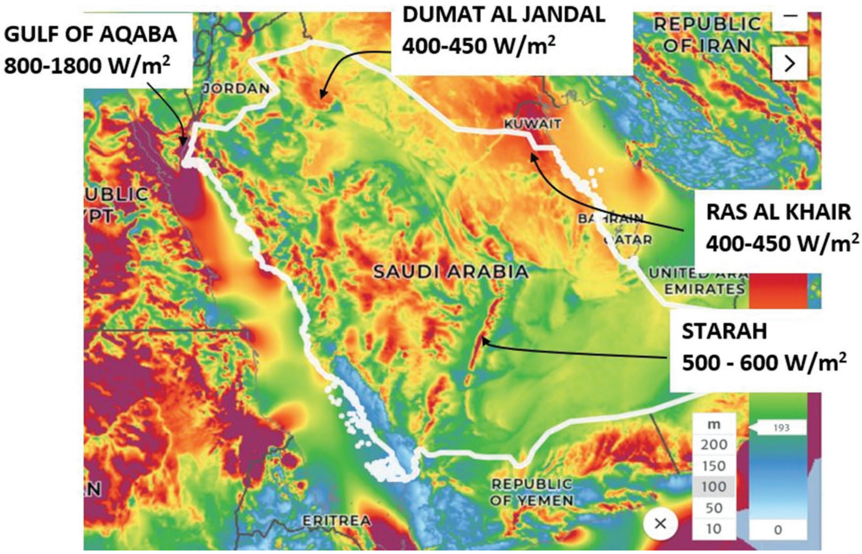

FIGURE 27.5 Examples of the available wind power densities at a height of 100 m.

Source: Global Wind Atlas 3.0.

When using batteries for energy buffering a cycle efficiency in the order of 0.75–0.80 may be considered. Li-ion batteries are well developed and relatively low in cost. However, those batteries have a limited life cycle in the range of 8–12 years, what has to be considered for the capital cost, since plants are commonly designed for 25–30 years life cycle. Also, ambient temperature condition in the Middle East region may have a negative impact on the life cycle of Li-ion batteries. Flow batteries which have currently a higher price, do have on the other side a significantly higher expected life cycle. Further developments of battery systems with higher cycle efficiency and/or lower cost may provide in future certain improvements.

When considering the production of hydrogen for energy buffering in combination with fuel cells, the cycle efficiency may be limited to about 0.45, which would be significantly lower than for batteries.

The shown gravity storage is a concept which is in an early development stage. A land-based gravity storage is anticipated to be lower in cost than current battery concepts while it may achieve a similar cycle efficiency (Energy Vault 2022) Similarly, a number of offshore gravity storage concepts are offered as well. Other options like hydro-storage may be suitable for energy buffering as well.

Besides possible concepts combining the SWRO desalination technology with wind and solar PV, concepts combining thermal desalination with thermal solar energy are available as well (Desolanator 2022). However, considering that capital costs for thermal desalination units with moderate PRs in the range of 10 kg/2,326 kJ are currently by a factor 2–3 higher than for the SWRO desalination systems, while cost of thermal solar systems in combination with required energy storage capacities is another high-cost factor in particular due to the high thermal energy consumption of thermal desalination systems in combination with the low CF of the thermal solar systems; it may be difficult to bring such concepts to a cost-competitive level for large capacity seawater desalination. However, those concepts may be suitable for special applications.

In general, if any desalination concept driven by renewable energy is considered to make an impact in the future desalination market, the achievable levelized cost of produced water will be the key factor.

Transitional approach

While the SWRO desalination technology gained over the past 10 years on reliability, allowing to replace the thermal desalination technology, large capacity thermal desalination plants like the 720,000 m^3/day Ras Al Khair MSF plant and the 550,000 m^3/day Yanbu 3 – MSF plant have been still built during this time.

Looking at the isolated desalination plants only, the significantly higher CO_2 emission of those MSF plants would make it desirable to replace them as soon as possible. However, they have with a remaining life cycle of 20–30 years a significant value, and the coupling with the power generation, as illustrated in Figure 27.2, does not allow a simple replacement. While older thermal desalination plants may be decommissioned together with the associated power generation systems, the abovementioned, relatively new MSF plants may be kept in operation for a longer period of time.

Considering in parallel, that in the next 10–20 years a significant green H_2 production capacity will be built up, which will need large quantities of water, the thermal desalination plants like the Ras Al Khair and Yanbu 3 MSF plants may be used to supply a high purity water which may be preferred for the H_2 production. While those plants are producing currently a distillate with a conductivity mostly in the range of 10–20 µS/cm, it may be possible to upgrade them with some simple modification to reduce the distillate conductivity further to a level of 2–5 µS/cm. This would elevate the value of those MSF plants and make it more acceptable to keep them for another 20 years in operation.

How green can hydrogen become when using water from desalination plants?

Considering that the operation of the entire hydrogen production facility will be operated by renewable energy and only an external water supply from an existing desalination plant would contribute to an allocatable CO_2 emission, the fractions of total energy consumption allocated to the hydrogen production and the related specific CO_2 emissions per kg of hydrogen as listed in Table 27.1 are tentatively

TABLE 27.1 Allocated energy consumption and CO_2 emission values

	PR	*LP steam*	*Convertible steam energy*	*Auxiliary power*	*Allocated Fuel consumption*	*Fraction of total energy consumption*	*Specific CO_2 emission*
	Kg/ 2,326 kJ	*bar*	*kWh/m³*	*kWh/m³*	*kWh/m³*	*% (1)**	*Kg CO_2/ kgH_2*
Thermal desalination	9–10	2.5	12–15	2–4	14–19	0.35–0.71	0.06–0.17
	9–10	4–5	15–20	2–4	17–24	0.43–0.90	0.07–0.22
SWRO desalination				3–4	3–4	0.08–0.15	0.01–0.04

(1)*Low value for water consumption 10 kg per kg of hydrogen: high value for water consumption 15 kg per kg of hydrogen.

applicable. Hereby, the allocated energy consumption and related CO_2 emissions are the highest for thermal desalination plants operating with higher steam supply pressure. The fraction of total energy consumption and specific CO_2 emission from water production allocated to the hydrogen production is dependent on convertible steam consumption, auxiliary power consumption, type of power plant, type of fuel (see hereto details described in "Desalination technology" subsection) and the assumed range of water consumption between 10 and 15 kg water per kg of hydrogen.

Considering scenarios as described in the previous sections, where SWRO plants could be in future connected to the grid which would comprise 50% renewable energy, or plants could be designed and operated with dedicated off-grid renewable power supply systems, the CO_2 emission of the water production could be reduced toward zero as well.

Environmental impact of brine discharge

Heat

'Thermal pollution' is a phenomenon worldwide associated primarily with power plants which may also affect any process where water is discharged at a significantly different temperature from ambient seawater. Elevated temperatures in the volume of water near the outfall will create a local environment that will be different from the natural one, possibly encouraging invasive species. Typical increases in discharged water temperatures are 5–10°C for thermal desalination/power plants and of order 1°C for membrane-based desalination plants (Abdul Wahab 2007, Jenkins and Wasyl 2005). On the Arabian Gulf coast of Saudi Arabia, it should be noted that surface water temperatures vary dramatically over the course of a year (between 18°C and 35°C). So local species are adapted to a wide range of temperatures and pockets of warmer water are unlikely to have the same impact that they would on an environment with a more stable temperature. Measurements of benthic plankton diversity in the near vicinity of a number of desalination plant outfalls off the coast of Israel showed a negative correlation between temperature elevation and number of species (Kenigsberg, Abramovich, and Hyams-Kaphzan 2020). T, with the highest biodiversity for an outfall with negligible temperature increase and the lowest for an outfall with 7.4°C average temperature increase (Kenigsberg, Abramovich, and Hyams-Kaphzan 2020).

Salinity

The susceptibility of marine organisms to salinity variations naturally varies from species to species and diverse results have been obtained from studies on different species in different parts of the world. Negative effects have been found on the growth rate of sensitive benthic species such as brittle stars measured within 500 m of SWRO desalination plant outfalls (Petersen 2017) and decreases in abundance and species diversity have been reported for polychaete worms (Fernández-Torquemada, González-Correa, and Sánchez-Lizaso 2013), echinoderms, molluscs, and oligochaete worms (Riera et al. 2012), and amphipods (Bagher Nabavi et al. 2013) in the immediate vicinity of desalination plant outfalls (<50 m). One investigation of seagrass beds in the immediate vicinity of a discharge point at a desalination plant in the Canary Islands found no indication of negative effects of increased salinity, with disrupted coverage due only to physical scouring from the entering water stream (Pérez Talavera and Quesada Ruiz 2001); another investigation found evidence of deteriorated plant health in Mediterranean seagrass beds in the vicinity of a SWRO outfall (Gacia et al. 2007). The Red Sea corals *Stylophora pistillata*, *Acropora tenusis*, and *Pocillopora verrucosa* were reported to suffer reduced growth in laboratory studies of salinity 10% above ambient (Petersen et al. 2018), while another Red Sea coral, *Fungia granulosa*, did not display any negative effects under similar conditions in the laboratory and in situ on the seabed (van der Merwe et al. 2014).

Benthic bacterial abundance has been found to be diminished markedly at salinities 5% above ambient at summer temperatures, though higher abundance was reported at the same salinity at winter temperatures (Frank 2017). Testing associated with the operation of seawater desalination plants in California and the Caribbean has indicated that while conditions may be suboptimal, most species can tolerate salinity of up to 20% above ambient values (Hammond et al. 1998). Bottom-dwelling organisms which have no ability to swim to regions of lower salinity tend to be more tolerant of salinity variations, surviving at levels elevated 40%–50% above ambient levels (Voutchkov et al. 2019).

Salinity measured at outfalls of modern desalination plants is typically less than 10% above ambient salinity values and the seabed area at which >5% salinity was expected (the limit for any negative effect to be found in the studies cited above) was calculated to vary between 0.04 and 0.12 km^2 for modern SWRO plants in Spain, Israel, Australia, and the United States (Frank, Rahav, and Bar-Zeev 2017). Thus, while it is undeniable that there are negative effects of increased salinity on marine life, they are highly localized and vary greatly depending on the species concerned and the local conditions.

Brine from thermal desalination plants is invariably mixed with power cooling water before discharge, reducing the salinity of the brine to less than 20% above ambient values. This is not possible with desalination methods not coupled with power generation, with brine from SWRO plants typically at least 50%–60% above ambient salinity at the point of entry. Thus, rapid mixing and dispersal using well-designed disperser systems are necessary to ensure seawater salinities are reduced to levels safe for all marine organisms within a short radius of the discharge point. This will become a more significant problem as technologies are pursued to give higher recovery, that is, more concentrated brine. While thermal technologies for desalination are not surprisingly more likely to generate negative effects by thermal pollution, the effects of increased salinity are more serious with membrane-based technologies.

Chemical footprint

Potential chemical issues that have been raised with brine discharge are three-fold. First, there is the issue of acidity. While thermal processes no longer use acidification to control scale formation, current SWRO processes used in the Kingdom of Saudi Arabia produce brine at a typical pH of 6.4–6.8, well below the alkalinity of the ocean. While seawater has a high buffer capacity, this will also have negative impacts on marine life within the near vicinity of the outfall. Transition to SWRO membranes that are more tolerant of alkaline pH, a process which is underway, will mitigate this concern.

Second, chemicals are added in levels of parts per million (ppm, mg/kg) – coagulants, anti-scalants, and anti-foaming agents.

The main coagulant used in desalination plant pretreatment is ferric chloride ($FeCl_3$); the synthetic polymers used in wastewater treatment plants (e.g., poly(diallyl dimethyl ammonium chloride) are rarely used. Iron chlorides form very insoluble iron hydroxide flocculant masses which are retained in the pretreatment and increase the iron concentration of the brine by only a few parts per billion (ppb, ng/kg) where used, polymeric coagulants are also quantitatively retained in flocculated particles in the pretreatment.

Anti-scalants are typically synthetic polymers of molar mass 1,500–2,500 g/mol, based on repeating carboxylic acid functionality (Fellows, Alhamzah, and East 2022). The most common anti-foaming agents used in the desalination industry are poly(ethylene oxide) alkyl ethers – this is a very common family of surfactants used in both industrial and household applications (Auerbach et al. 1981, Imam et al. 2000). Both anti-scalants and anti-foaming agents will remain in the discharged brine at typical concentrations of about 2 ppm. Anti-scalants and anti-foaming agents by their nature are associated with interfaces: anti-scalants not retained on the surface of colloidal particulates within the brine will adhere to colloidal particulates in seawater and end up in the sediments at ppb levels. These compounds, being high-molar mass, are biologically inert. Historically, phosphate-based anti-scalants have been used, which can generate phosphate – a limiting nutrient associated with eutrophication – on decomposition. These anti-scalants have been phased out for thermal plants due to their ineffectiveness at high temperatures, but may have a marginal effect on environments exposed to SWRO brines. Anti-foam agents discharged in brine at ppm levels will be concentrated on the air-water interface, a complex environment dominated by surface-active molecules of biological origin. The potential impact of these compounds has not been investigated but they will be present at lower levels than other anthropogenic surface-active species found in the surface film of near-shore water derived from run-off and maritime activities (Astrahan 2018).

Third, the prospect of heavy metal contamination by corrosion products of desalination plants has been raised. It is potentially possible that a desalination plant could be run in such a poor manner that this could occur, but it would cease operation in a short time due to the many negative effects of corrosion. Trace metal concentrations in the vicinity of the desalination plants operated by the Saline Water Conversion Corporation have been monitored for the past twenty years and occasional spikes in concentration of copper and iron observed have been traced to maritime activity and not to corrosion by-products.

Table 27.2 compares the chemical usage for typical SWRO and thermally systems, currently and potentially.

It can be seen that quantitatively the biggest issue is chemicals required for pH control. Sodium hydroxide and hydrochloric acid are generated by electrolysis of sodium chloride solution while sulfuric acid is generated by oxidation of sulfur; both processes are energy intensive and must be accounted for in the overall environmental assessment of desalination operations.

Future environmental impact of brine discharge

A number of issues have been raised with respect to the environmental impact of brine discharge. Key to addressing these issues is efficient dispersion of the brine discharge: while discharge into a restricted body of water with poor circulation can convert it into a "dead zone," even in a body of water such as Cockburn Sound in Western Australia, with relatively sluggish circulation, outfall design ensures that brine is diluted by a factor of 45 within 30 m of the discharge point (Voutchkov et al. 2019). All the desalination plants currently operating in the Kingdom of Saudi Arabia discharge brine into well-circulated water such that water samples fall within the ambient range of quality parameters within 100–300 m of the discharge point. Thus, while the potential impacts of brine discharge should be monitored and reasonable steps taken to minimize them, it should be emphasized they are minor stressors of the near-shore Arabian Gulf and Red Sea environments in comparison to land reclamation, plastic waste, and stormwater runoff.

Future changes in environmental impact expected with changing desalination practice are mostly minor and positive, with one major potential negative change. The shift to RO rather than thermal processes will decrease the potential issues of thermal pollution, contamination by ppb levels of corrosion products, and contamination by ppm levels of synthetic polymers (as low-temperature operations are more suitable to use of biodegradable anti-scalants and anti-foams). The shift in

TABLE 27.2 Approximate current and projected future chemical usage for seawater desalination plants operating on the Arabian Gulf

Chemical (tonnes/ billion m³ product water)	*RO current*	*RO future*	*Thermal current (MSF)*	*Thermal future (next generation MED)*	*Maximum potential concentration in brine (ppm)*	*Notes*
Sulfuric acid	66,000	0	0	0	0	Used for pH control; unnecessary with more resistant membranes
Carbon dioxide	50,000	36,000	50,000	36,000	Will be a function of pH, T, ionic strength, and total concentration of carbonate species	Used for remineralization to achieve optimum hardness and alkalinity; potentially reducible with more efficient contactors
Limestone	45,000	45,000	35,000	35,000	0	Used for remineralization to achieve optimum hardness and alkalinity; potentially reducible with more efficient contactors and the application of salts derived from brine for magnesium supplementation
Sodium hydroxide	35,000	40,000	36,000	26,000	0	Used for remineralization to achieve the optimum hardness and alkalinity, and for boiler water treatment; potentially reducible with more efficient contactors, but will be required to generate a magnesium hydroxide coagulant
Ferric chloride	27,000	0	0	0	2022: 2 Future: 0	Can be replaced with magnesium hydroxide coagulant obtained from desalination brine
Anti-scalant	0	1,000	7,500	4,000 Future: 8 No chemical hazard	2022: 12	Higher recovery ratios in future RO are likely to require next generation anti-scalants; these will also be effective at lower concentrations

Sodium metabisulfite	3,000	500	0	0	0	Chlorine scavenger; more resistant membranes and more adaptive inline monitoring of intake will make it redundant except for occasional events; small amount used in membrane clean-in-place (CIP) systems
Sodium sulfite	0	0	2,500	2,500	0	Oxygen scavenger
Citric acid	1,500	1,000	0	0	0	For CIP; greater efficiencies in cleaning frequency expected
Ammonium hydroxide	450	300	0	0	0	
Tetrasodium ethylenediamine tetraacetic acid (Na_4EDTA)	420	280	0	0	0	
Chlorine	400	0	400	0	0	Disinfectant in posttreatment; to be replaced by new technologies (e.g., ozonation)
Hydrochloric acid	0	0	250	200	0	For boiler water treatment and removal of inorganic scale
Antifoam	0	0	250	200	2022: 0.4 Future: 0.4 No chemical hazard	
Helamin	0	0	180	180	0	Corrosion inhibitor for boiler water
Detergent	0	0	150	100	0	For power plant
Sodium benzoate	75	50	0	0	0	For CIP; greater efficiencies in cleaning frequency expected
Cationic flocculant	60	40	0	0	0	For wastewater treatment
Anionic flocculant	30	20	2	2	0	
Calcium hypochlorite	0	0	10	2	0	
Aluminum sulfate	0	0	2	2	0	

Source: Data from the Ras al Khair thermal and reverse osmosis desalination plants, Saudi Arabia courtesy of Zaher Al-Rabai.

the Kingdom from hollow-fiber RO membranes to spiral-wound RO membranes, which are less sensitive to pH. Will decrease the environmental footprint of desalination by reducing high-volume chemical use for pH adjustment. However, the shift to RO, and to processes with ever higher recovery, will also lead to the discharge of significantly more concentrated brines. These will need to be monitored more carefully for salinity impacts on the marine environment and may require more complex and expensive outfall design.

Research and development

In the field of seawater desalination, the optimization of the SWRO technology reached a point where little room is left for a further reduction of energy consumption.

Besides the membrane technology, there are currently no desalination technologies on the horizon, which would promise to provide a significant improvement.

Considering the development of desalination technologies toward green desalination, there is a wide range of system optimization required. Influencing factors for the future optimization of green desalination systems are, further developments of solar PV panels, development of wind turbines with high CF for moderate wind power densities, capital cost of those components, different storage solutions, and SWRO membranes which are allowing a wide range of load variations. Furthermore, with the use of renewable energy, each individual project will have to be optimized based on locally available solar and wind energy, which will add a significant complexity to the design and optimization of future desalination plants. While in the field of seawater desalination, the optimization of the SWRO technology has reached a point where little room is left for a further reduction of energy consumption.

There are potential benefits to be gained in more advanced use of chemicals (Table 27.1).

The largest use of chemicals in desalination in terms of environmental footprint are the acids and bases used for pH adjustment; in the Kingdom of Saudi Arabia, these are chiefly sulfuric acid for reducing pH for enhancing membrane lifetime and performance, and sodium hydroxide for achieving a final product water pH giving a Langelier Saturation Index (LSI) between 0.1 and 0.3 in order to avoid corrosion of transmission systems. The use of more efficient remineralization systems where an excess of carbon dioxide is avoided in the dissolution of limestone should significantly reduce the use of sodium hydroxide.

Another significant input of chemicals in the SWRO process is the use of ferric chloride or ferric sulfate coagulant. There is some evidence that magnesium hydroxide can be equally effective for this purpose, and this is an area where research and development is required. Magnesium hydroxide is attractive for this purpose not only because it avoids the potential issues of fouling and biofouling arising from coagulant overdosing but because it can be sourced sustainably on site from desalination brine. While this can be done most simply by treating brine with sodium hydroxide (Table 27.1), it should be possible to generate it by using ammonia, a key component of the hydrogen economy which would be available at an integrated hydrogen generation facility.

Continued research into anti-scalants for SWRO to replace the remaining use of phosphate-containing products in formulations with other species that pose no risk of adding phosphate to the environment would provide a small but real improvement in environmental impact of desalination.

Case study

Efforts toward reduction of CO_2 emissions are made with new desalination projects, built together with solar PV plants to produce renewable energy consumed by those desalination plants like at the Al Khafji and the Yanbu 4 SWRO desalination plants. Further steps are made toward green seawater desalination considering off-grid renewable power supply for desalination plants as illustrated for example in the second section. The optimization of desalination and renewable energy for NEOM city is another example (Riera et al. 2022).

Conclusion

The nature of the water supply system in the Kingdom of Saudi Arabia is such that seawater desalination is the only sustainable high-volume source of quality water for hydrogen generation. Surface and underground water sources in Saudi Arabia, while having a lower content of solids than seawater and thus having a smaller processing cost, are geographically dispersed and heavily over-used for agricultural purposes. In the vicinity of urban areas in particular, underground water sources in the Kingdom have typically seen a precipitous decline in quantity and quality over the past fifty years. The unconstrained volume of water which can be produced by seawater desalination at a point source, the consistent quality achievable, and the location of desalination plants relative to industrial areas, all make it the only viable source for water for hydrogen production in Saudi Arabia. While Saudi Arabia has under the VISION 2030, the NREP, and the Saudi Green Initiative the goal toward a significant reduction of CO_2 emissions, it will in a transitional period remain that not all produced hydrogen will be green hydrogen. Similarly, not all produced desalinated water will be green water. However, efforts are made where the average energy consumption for desalination plants is getting drastically reduced by replacing thermal desalination systems by SWRO technology. Further, the country's goal to produce 50% of its grid power by renewable energy will reduce the allocated CO_2 emissions of SWRO plants.

The total amount of water assumed to be required for the foreseen green hydrogen production would consume about 1% of the water produced by desalination plants. Comparing the allocatable average CO_2 emission of future desalination systems to a hydrogen production by electrolysis operating with electric power generated by fossil fuels, the contribution of CO_2 emission from the desalination process to the hydrogen production would be below 0.1% or in the range of 0.01–0.04 kg of CO_2 per kg of H_20. Would a zero CO_2 emission for the water consumed for the hydrogen production be preferred, it would be technically feasible to integrate a SWRO desalination system into a hydrogen production facility and operate it like the hydrogen production with renewable energy only.

Note

1 The ratio of annual actual output divided by the theoretical output if a system runs constant at design capacity.

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28

THE CLEAN HYDROGEN ECONOMY AND SAUDI ARABIA

Findings and final thoughts

Saumitra Saxena, Jan Frederik Braun, Rami Shabaneh and Jitendra Roychoudhury

This book analyzes the drivers of hydrogen development in Saudi Arabia and the Kingdom's efforts to establish itself as a major player in the nascent clean hydrogen economy. In addition, it examines the global hydrogen economy by discussing those countries and regions that, for various reasons, are perceived to play a major role in shaping the future market for hydrogen and thus become important to the Kingdom. Finally, the book describes the relevant potential technological pathways by exploring, in depth, the research, development, deployment, and innovation efforts and plans by academia and industry for the Kingdom to become a global hydrogen leader. The domestic, international, and research aspects of the analysis are structured as follows:

- Part 1: The clean hydrogen economy and Saudi Arabia: Domestic developments
- Part 2: The clean hydrogen economy and Saudi Arabia: International opportunities and challenges
- Part 3: The clean hydrogen economy and Saudi Arabia: Hydrogen technologies

Combined, the three parts of this book and its analytical framework provide a sound grounding for understanding the different aspects of the hydrogen economy in Saudi Arabia, including its interests, opportunities, and challenges domestically and internationally. In the following sections, we discuss the main findings from Parts 1–3 and discuss developments and opportunities beyond the scope of the chapters on Saudi Arabia's role in the nascent clean hydrogen economy.

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Part 1: The clean hydrogen economy and Saudi Arabia: Domestic developments

The main question for Part 1 was

- **What are the challenges and opportunities for Saudi Arabia in the domestic field of clean hydrogen?**

In an increasingly carbon-constrained world characterized by a wave of net-zero targets from governments and industries, the Kingdom faces certain challenges and opportunities regarding clean hydrogen. These challenges, detailed in Part 1, are summarized in Table 28.1.

Rami Shabaneh and Jan Frederik Braun point out in **Chapter 2** that Saudi Arabia is an ideal region for developing clean hydrogen projects. Among the reasons are its low-levelized electricity costs, ample solar and wind resources, and large available land areas. The Kingdom also benefits from the availability of low-cost natural gas (including the low methane intensity of its supply chain), ability to store large amounts of CO_2, and proximity to European and Asian markets. However, although these characteristics are good starting points, clear incentive mechanisms are required to foster investment and run clean hydrogen projects.

Therefore, the authors emphasize the need to implement clean hydrogen development policies and create a conducive environment in which a domestic hydrogen market can develop and expand its production for export. Saudi Arabia's hydrogen strategy focuses on the key elements of the value chain, including the production, exports, and domestic use of clean hydrogen as well as the infrastructure

TABLE 28.1 The opportunities and challenges regarding clean hydrogen for Saudi Arabia

Opportunities	**Diversification:** Meeting several key mandates of Saudi Vision 2030, which include diversifying the country's exports and leveraging existing sectors' supply chains to increase local value creation
	Circular carbon economy (CCE): Considering clean hydrogen as a cross-cutting component of the CCE framework, especially as a critical enabler in decarbonizing hard-to-abate sectors
	Industrial expertise: Capitalizing on existing expertise, trade routes, and supply chain capacities to produce hydrogen and chemicals at an industrial scale as well as capture and store CO_2
Challenges	**Regulatory framework:** Regulating the licensing, distribution, and pricing of hydrogen projects, for which no legislation is currently applicable
	System integration: Rapidly developing a renewable hydrogen value chain, including infrastructure, human capital, and demand
	Research, development, demonstration, and innovation (RDD&I) competition: Creating a dynamic and competitive institutional capacity in RDD&I along the hydrogen value chain by applying academic research to industrial deployment and related manufacturing capacities

and transport sectors. To drive policy forward, the Kingdom has signed bilateral agreements with multiple countries to accelerate knowledge exchange throughout the value chain, develop technical standards for hydrogen-fueled vehicles, and establish a certification framework to support hydrogen investments and trade. In addition, the CCE framework, which reflects a technology-agnostic approach to achieve net-zero goals, provides a significant opportunity to develop clean hydrogen. A clearly defined CCE taxonomy and its consistent use in a national CCE program can provide regulatory clarity on the cross-cutting role of clean hydrogen. This would have substantial appeal as a policy approach for other fossil fuel exporters within and beyond the Gulf region.

Regarding governance, hydrogen is the main pillar of the Kingdom's integrated energy strategy. This strategy aims for hydrogen to compete globally on costs and carbon abatement. It also acts as an enabler to extract value for the Kingdom in terms of innovation, human capital development, and localization. The authors recommend adopting a balanced approach to developing clean hydrogen. "Parallel strategies" would allow the Saudi government to use its expertise, infrastructure, and production capacity in blue hydrogen in the hydrocarbon-rich areas of the country while it simultaneously develops an industrial-scale green hydrogen-based value chain. As part of effective policy planning in the Kingdom, it is equally important to consider sustainability criteria other than greenhouse gas emission intensity to avoid other negative externalities associated with hydrogen production. These include land, water, and energy. These aspects strengthen the government's net-zero by 2060 ambition and the Saudi Vision 2030s economic diversification aims by making the Kingdom's domestic hydrogen industry internationally competitive in terms of both cost and sustainability.

Beyond the scope of Chapter 2, as decarbonization efforts increase, the role of the government and state-owned enterprises will become important in terms of inducing private capital and pushing hydrogen projects. The Public Investment Fund (PIF), among the largest sovereign wealth funds in the world, is a driving force in the diversification and growth in Saudi Arabia's non-oil GDP. Further, it has become the primary vehicle for realizing the Kingdom's vision of reaching net-zero emissions by 2060. The PIF is also one of six founding members of the One Planet Sovereign Wealth Fund Working Group established in 2017 to accelerate the integration of financial risks related to climate change into large long-term asset pools (OPSWFN 2017). The PIF has since published its Green Finance Framework to enhance the coverage of environmental, social, and governance factors and unlock new sustainable sectors in the Kingdom (PIF 2022). This framework provides a basis for issuing green bonds and other suitable debt instruments to fund eligible green projects, including renewable energy, green hydrogen, energy efficiency, and sustainable water management. However, it is important not to crowd out small and medium-sized enterprises (SMEs) to develop parts of the supply chain and create long-term employment prospects where many of the opportunities to develop a local hydrogen economy reside.

Jim Krane and Jan Frederik Braun describe in **Chapter 3** that hydrogen plays a major role in Saudi Aramco's economic diversification plans. As the world's lowest cost, high-volume producer of crude oil and natural gas, Aramco has an integrated and complementary infrastructure at scale. In particular, it possesses significant know-how in carbon capture, utilization, and storage (CCUS) and holds a leading position in global ammonia trade owing to its majority stake in SABIC (Chapter 4). Aramco therefore has a strong opportunity to establish a competitive presence in the nascent clean hydrogen market. In addition, during the energy transition, producers such as Aramco can still export oil and gas and benefit from the generated rents while simultaneously improving the return on decarbonized products such as hydrogen. Another factor encouraging Aramco's hydrogen investment is the probability that demand for hydrogen will increasingly be negatively correlated with demand for oil and positively correlated with success in decarbonization. Aramco's extensive oil and gas infrastructure in Saudi Arabia's Eastern Province, including its high carbon sequestration potential, can be leveraged to produce large volumes of blue hydrogen. The most advanced infrastructure will be the CCUS hub in Jubail, which has a planned annual capacity of 9 million tonnes and is slated to come online in 2027. This will be the first phase in the development of the Kingdom's planned 44 million tonnes of annual carbon capture capacity by 2035 and will help Aramco become a major producer of blue ammonia. Aramco also plans to deploy utility-scale renewable energy plants and invest in green hydrogen technology and production capacity. The authors also point out that the Eastern Province has enormous potential for the optimal production of green hydrogen.

Aramco's focus on clean hydrogen as part of its diversification and decarbonization is considered by the authors as a crucial variable in the effectiveness of the Kingdom's national and global climate action. The company is the world's largest integrated energy and chemicals company and a substantial contributor to direct—and especially—indirect atmospheric emissions. The authors discuss Aramco's mixed signals about its commitment to diversification and energy transition-related technologies. On the one hand, a range of announcements underline its ambition to become a major player in the clean hydrogen market. However, Aramco allocates lesser capital spending to the energy transition than other major oil and gas companies. The authors also state the importance of mitigating Scope 1 and Scope 2 emissions, particularly reducing methane emissions. Nonetheless, Scope 3 emissions, or indirect emissions from fuel combustion, are just as important to address. Taking stock of its Scope 3 emissions is not only relevant for Aramco's conventional operations but also serves its clean hydrogen ambitions, where hydrogen exports can significantly reduce its Scope 3 footprint. It must also compete on costs, strict sustainability criteria, and transparent carbon accounting throughout the value chain. The authors conclude that only then will Aramco be able to sell itself internationally as a provider of clean energy solutions.

Aramco's acquisition of SABIC expanded its downstream footprint and increased synergies throughout the hydrogen value chain, as chemical plants, including ammonia and methanol production facilities, can be integrated with new and existing carbon capture infrastructures. Abdulaziz Aljodai, Pieter Smeets, Fahad Al Shehery, and Hicham Idriss further explain in **Chapter 4** that similar to Aramco, SABIC has a net-zero by 2050 target. To achieve this target, SABIC intends to decarbonize its operations through a combination of increased renewable energy installations and hydrogen as a chemical feedstock. SABIC has successfully piloted shipments of blue ammonia to Japan and South Korea. This has helped increase its knowledge of carbon emissions across the production chain and provided an opportunity for the certification of such shipments. It has also allowed the development of business models for trading clean hydrogen and its derivatives, thus feeding into a business implementation of the CCE framework and helping achieve Saudi Vision 2030.

According to Frank Wouters (**Chapter 5**), the NEOM region in northwest Saudi Arabia has an ambitious plan to become a leading producer of green hydrogen as well as a hub of knowledge and innovation. The NEOM Green Hydrogen Company's 1.2 million tonnes/annum green ammonia plant is the region's first step toward achieving its hydrogen ambitions. NEOM has "various scenarios that go all the way from 15 GW to 30 GW of installed electrolyzer capacity," depending on growth patterns and the success in attracting advanced industries into the city (Carpenter 2021). The consortium behind the NEOM Green Hydrogen Company, which is aiming to develop more projects close to the plant at NEOM, is confident that the costs of new plants will fall as developers become more experienced, technology improves, and a local supply chain develops (Martin and Abuljadayel 2023). One consortium member, ACWA Power, is confident that demand for fuel will rise as governments and companies accelerate plans to reduce their carbon emissions. Indeed, ACWA Power is receiving support from the Saudi government through SHAREEK, a public–private partnership program that aims to encourage firms to invest in the development of new domestic industries (Martin and Abuljadayel 2023).

Scaling up its hydrogen production capacity will become NEOM's major goal for realizing its hydrogen-based ecosystem. This will also be a challenge, as for any renewable energy capacity required for hydrogen, the many gigawatts of renewable power for NEOM's electricity system in a region that aims to minimize its ecological footprint must be considered. An additional challenge is that the NEOM region has little to no industrial-scale production, demand, and infrastructure available for using its hydrogen. Moreover, for the Kingdom's export purposes, it will need to build an industry from scratch—and quickly.

In addition to creating economies of scale, NEOM is aiming to become a hub for research and innovation in hydrogen development by linking industrial actors with applied research and technical institutions. Fields for innovation could include novel hydrogen storage solutions, fuel cells, electrolyzers, and hydrogen-related components. Alternatively, it could include the production of more complex fuels such as synthetic kerosene, which could be used with direct air capture.

NEOM could also reduce the cost of electrolyzers by becoming a manufacturing hub for electrolyzer assembly or hydrogen value chain components. Further green hydrogen-based applications that could be developed in NEOM include energy balancing systems (e.g., to serve NEOM's variable renewables-based electricity system), the production of fuel cell-powered commercial vehicles and other mobility options, and fuel cells for off-grid energy supply.

In summary, NEOM is seeking to become a hydrogen hub at the intersection of science and business. In this capacity, it is a central pillar of Saudi Arabia's ambition to capture a substantial share of the nascent knowledge- and innovation-based green hydrogen economy.

Saumitra Saxena, Bassam Dally, Kevin Cullen, and William L. Roberts emphasize in **Chapter 6** that for hydrogen to become the energy vector of choice in the future, an RDD&I ecosystem must be implemented worldwide, including in Saudi Arabia. A substantial proportion of these activities occur in universities and research institutions. Building a robust ecosystem is thus crucial for the large-scale penetration of the hydrogen economy; such an ecosystem would be technologically agnostic and encourage other fields of science and technology. The framework developed by the King Abdullah University for Science and Technology (KAUST) for translating university research into economic goals (the knowledge exchange model) was explored to accomplish innovation objectives. Such a model could be indispensable to politicians, policymakers, and researchers seeking to efficiently translate university research for the public's benefit—not only for the hydrogen economy but also for all research of national and global importance.

One of the best mechanisms for measuring technological innovation is patent filing. Several agencies have conducted patent analyses on hydrogen and related technologies, most notably IP Australia, the International Energy Agency, and the European Patent Office. Figure 28.1 shows the types and locations of hydrogen development.

Figure 28.1 shows both the challenges and opportunities for Saudi Arabia. The challenge is that patenting over the past decade has been highly concentrated in selected groups of countries, including the European Union (EU) member states. The patenting pattern also highlights the risk of the mismatch in supply and demand technologies, showing that the surge in patent filings around hydrogen production must be accompanied by advances in hydrogen storage, distribution, and applications (IP Australia 2021; IEA and EPO 2023). The uneven trend in patent filings between end uses and production is an opportunity for innovation hubs such as NEOM. An early focus on innovation in end-use applications could strengthen Saudi Arabia's capacity to capture substantial value in the hydrogen economy in a structural manner.

Another lesson that can be drawn from the contributions to Part 1 is that the Saudi government and its key stakeholders in the hydrogen economy understand the unique aspects of the hydrogen value chain. As described in the Introduction, they are fostering a wide range of international government-to-government and business-to-business collaborations to create economies of scale, particularly with stakeholders from regions with the potential to import. These collaborations cover supply chains, technological innovation, infrastructure, and market development. To drive domestic development in the hydrogen sector, Part 1 also points out the

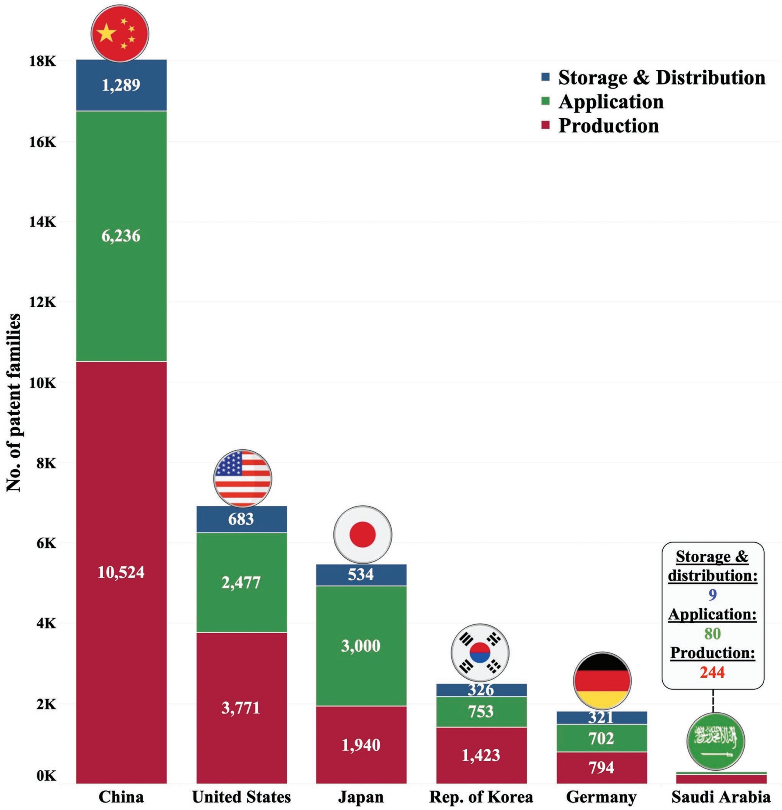

FIGURE 28.1 Leading countries' patent families in hydrogen-related technologies. The graph shows patents filed, accepted, or granted during 2010–2020 by origin.

Source: IP Australia (2021).

importance of focusing on creating local demand via hubs as well as leveraging these activities to expand into new sectors.

Part 2: The clean hydrogen economy and Saudi Arabia: international opportunities and challenges

The main questions for Part 2 were

i **What are the challenges and opportunities for Saudi Arabia in the international field of clean hydrogen?**
ii **Which countries and regions relevant to Saudi Arabia are working on clean hydrogen and for what purposes?**

Regarding (i), the main challenges and opportunities for Saudi Arabia taken from Part 2 are summarized in Table 28.2.

TABLE 28.2 The opportunities and challenges for Saudi Arabia as an international player in clean hydrogen

Opportunities	**Resource monetization:** Using hydrogen derived from fossil fuels as an opportunity to capitalize on the Kingdom's oil and gas reserves as demand starts to reduce due to the transition away from carbon-based fuels **Established energy partnerships:** Leveraging established energy and industrial partnerships, major offtake markets in Asia and Europe can provide ample opportunities for collaboration throughout the value chain **Global scale-up:** Scaling up hydrogen value chains (including CCUS technologies), fueled by the clean-tech leadership race between Europe, the United States, Middle East and North Africa (MENA) countries, and China could have spillover benefits for advancing technology and reducing costs
Challenges	**Competitive landscape:** A competitive environment for clean hydrogen production and exports as other cost-competitive regions with favorable policies are emerging **Demand uncertainty:** Recognizing that the future trajectory of global hydrogen demand is uncertain and will depend on the cost of hydrogen technologies compared with that of other low-carbon solutions as well as the development of regulatory frameworks and infrastructures **Divergence in hydrogen standards:** Understanding that dissimilar national standards and codes for clean hydrogen can hinder international trade

This section clarifies that the global race for clean hydrogen leadership has ensued in various countries and regions. The EU was the first to recognize the importance of green hydrogen in its 2020 hydrogen strategy. The formulation of that strategy and implementation of subsequent policy instruments have facilitated its access to financial support (including a Hydrogen Bank) and support from the RDD&I of electrolysis technology. However, other countries have quickly caught up, as shown in this section. The United States has passed the Inflation Reduction Act, which includes a generous tax credit for clean hydrogen production. The Chinese government has laid out a medium- and long-term development plan for clean hydrogen with major policy support. Finally, Australia's hydrogen and derivatives industry investment pipeline represents approximately 40% of all global renewable hydrogen projects (Australian Government 2023).

In summary, Saudi Arabia faces serious competition from the other countries in the hydrogen race taking substantial measures to stimulate their production and export capacities. Rapidly implementing policy incentives, creating an attractive business environment, and pursuing international collaborations that contribute to value creation domestically in the long term can help Saudi Arabia gain traction in such a nascent market. Further, the underlying interests of countries and regions in a clean hydrogen economy are predominantly based on achieving economic gains, yet almost always in conjunction with climate change mitigation.

Overall, globally, the momentum building behind clean hydrogen since the signing of the Paris Agreement has been tremendous. The countries discussed here have all announced roadmaps and cooperation agreements to make hydrogen part of their decarbonization plans. However, clearly defining the role of clean hydrogen in a national net-zero economy, for example, in terms of strict and measurable targets that are reviewed annually, will be a challenge for all countries vying for international leadership in this area. International developments in climate change will be an important variable for countries investing in the hydrogen economy. They will need to compete not only on costs per kilogram of hydrogen but also on the ability to adhere to (increasingly) strict sustainability criteria throughout the value chain.

This brings us to the challenge of establishing consistency in international standards, codes, and regulations throughout the supply chain to promote the widespread use of hydrogen as an energy carrier. The main goal is to achieve an acceptable level of safety and quality in hydrogen systems, as these must be integrated into the national economy. It is also important to establish an interoperable certification system to track the carbon intensity of each component of the hydrogen value chain compatible with different methodologies from the different regulatory frameworks worldwide.[1]

Establishing this type of international consensus is important to facilitate project development, ensure financing, and scale up hydrogen to achieve the cost reductions required to create a hydrogen economy within and beyond Saudi Arabia. However, because of the absence of a global hydrogen market, the standardization of new hydrogen applications is vulnerable to trial and error as learning from initial deployments takes place. Trial and error will be necessary, as no initial approach will be foolproof and valuable lessons can be learned.

In Saudi Arabia, the Saudi Standards, Metrology, and Quality Organization (SASO) is the official body responsible for approving mandatory safety and quality standards. In March 2022, SASO laid out technical regulations for hydrogen-powered vehicles, including propulsion, onboard storage, and monitoring systems (SASO 2022). The SASO standards conform to existing hydrogen-related ISO standards, including the fueling infrastructure, protocols, and hydrogen vehicle fueling equipment. However, in terms of trade, hydrogen quality standards will need to conform to those of other regions as international trade expands. For example, the threshold for blending hydrogen into natural gas networks and compatibility with some end-use appliances can vary widely, particularly in the cross-border regional pipeline trade. These differences can serve as barriers to hydrogen trade internationally (IEA 2020).

Safety standards for hydrogen materials and equipment must be ensured, maintained, and updated periodically to avoid leakage and other issues. Not only is hydrogen a fire hazard, but recent studies have also highlighted its indirect impacts on climate change. Venting hydrogen into the atmosphere can prolong the lifetime of methane, which may partially offset its environmental benefits (Warwick et al. 2022). Safety standards should also be extended to the handling of hydrogen derivatives such as ammonia and methanol, which are likely to be the hydrogen carriers of choice and applied directly as an energy vector. Both ammonia and methanol are toxic and must be handled with care. However, established standards and experiences related to how the industrial sector handles chemicals must be transferred and tailored to other industries.

Regions and countries that wish to integrate clean hydrogen into their economies are developing standards to define clean hydrogen, similar to safety and quality standards. These standards typically mirror the regulatory framework of the country or region and can include a number of sustainability criteria. Such criteria could include greenhouse gas emissions thresholds, system boundaries for calculating greenhouse gas emissions, the type of energy consumption, and tracking models[2] (i.e., mass balance or book and claim). Certification becomes mandatory to demonstrate compliance with the regulatory framework to receive government aid (e.g., tax credits and subsidies) or count toward a region's clean hydrogen target (Sailer et al. 2022). Because hydrogen can be produced through multiple pathways, it is important for suppliers to verify its attributes to inform consumers of the hydrogen they are procuring. Certification builds consumer trust, stimulates demand, and facilitates cross-border trade. However, regulations are still being developed in many parts of the world and a globally accepted certification system is lacking.

In the United States, clean hydrogen developers can receive different incentives if their plant's carbon intensity is below 4 $kgCO_2/kgH_2$, regardless of the production technology used. Regulations in Europe are more skewed toward green hydrogen and can have different rules on how renewable electricity is consumed and where CO_2 can be sourced for hydrogen-derived power fuels. Thus, the differences in clean hydrogen standards can pose an investment risk for hydrogen project developers. This is particularly the case in potential exporting countries such as Saudi Arabia, where the plant design may allow hydrogen to be sold in some import markets but not in others.

Several studies have compared the hydrogen certification schemes being developed globally. They find that there is divergence in standards and it can be challenging to harmonize them across all certification schemes without abandoning certain requirements (Sailer et al. 2022; IRENA and RMI 2023). This divergence in standards can result in a fragmented market for hydrogen, leading to a less liquid market and slow ramp-up in production, thereby impacting the growth of hydrogen adoption. Intergovernmental bodies such as the International Partnership for Hydrogen and Fuel Cells in the Economy are facilitating international cooperation and providing recommendations on safety standards and emission calculation methodologies for producing hydrogen (IPHE 2021). Collaborating on this aspect is crucial, as producers and off-takers must work on a mechanism sufficiently flexible to allow for changes in end-use markets. Actively engaging in certification discussions in these and other international forums would allow the Kingdom to shape ongoing discussions on this topic (Braun and Shabaneh 2021). In turn, these efforts would serve to strengthen government-to-government and business-to-government partnerships with major importers, as mentioned in this book.

The Ministry of Energy of Saudi Arabia has created a taskforce to develop a certification framework that is inclusive and accepted by target markets. Its objective is to establish national criteria and adopt an inclusive certification scheme that encompasses all carbon-neutral production pathways, in line with the CCE framework adopted by the Kingdom. In addition, part of this framework recognizes the regulations in other import markets and identifies ways to align them with their criteria.

With strategies and governance mechanisms for hydrogen ecosystems under development, it is important to recognize the activities that occur outside Saudi Arabia and understand how countries appraise the hydrogen economy from their perspective. The following section summarizes some chapters of Part 2 and explains which countries and regions relevant to Saudi Arabia are working on clean hydrogen and for what purposes. In addition, the summaries include observations from the fast-moving world of the hydrogen economy, which is beyond the scope of the chapters, but relevant to Saudi Arabia.

Middle East and North Africa

According to **Chapter 7** by Wa‘el Almazeedi, the MENA region possesses the resources necessary to produce clean hydrogen. The author identifies five countries that have emerged as early hydrogen movers in this region: Egypt, Morocco, Oman, Saudi Arabia, and the UAE. All five are early movers in terms of ramping up clean hydrogen and ammonia projects in partnership with international companies or finalizing hydrogen roadmaps and strategies in collaboration with major demand centers. These early movers dominate projects operating or under development in the MENA region. They are driven by different objectives such as substituting imports, prolonging the life of hydrocarbon reserves, and expanding their commodity export portfolios. Moreover, they are expected to leverage their unique resource endowments, technical competencies, institutional capacities, and competitive positioning both regionally and globally. This should expedite and enhance the effectiveness of their planned strategy implementation.

For some MENA countries, hydrogen may be the most cost-effective response to the energy transition and may avoid the high risk of rendering a sizable proportion of their hydrocarbon reserves stranded. In addition, all these early MENA movers face huge challenges in realizing their hydrogen economy ambitions. The first challenge that Al-Mazeedi points out is that the business model for hydrogen will differ from that for oil in that it will be characterized by a different market structure that will be complementary to electricity. The second challenge is the effort required to install renewable electricity capacity to lower the carbon intensity of the power sector and hydrogen production. Third, incentive schemes and appropriate regulatory measures are required to develop hydrogen hubs and CCUS for domestic demand creation and export. Finally, Al-Mazeedi underlines the importance of promoting and institutionalizing the Saudi-initiated CCE framework across the MENA region for low-carbon hydrogen to be considered a sustainable decarbonization option. Again, this will require substantial and effective regulatory frameworks that not only promote the production and offtake of clean hydrogen but also ensure that the captured carbon is used to manufacture advanced materials for energy transition applications.

Al-Mazeedi presents a roadmap for Saudi Arabia and other MENA countries to tackle these challenges and allow them to compete during the energy transition using clean hydrogen as a catalyst. The key aspects of this roadmap are as follows:

- Scaling up commercially available state-of-the-art low-carbon hydrogen production technologies
- Creating local demand applications for low-carbon hydrogen and rolling out the required infrastructure (including storage capacity)
- Facilitating financing for first-of-a-kind hydrogen and CCUS projects
- Developing efficient and well-functioning markets for merchant hydrogen and its derivatives to enable trading and matching supplies with offtakes
- Demonstrating key precompetitive technologies with the potential to improve sustainability and reduce hydrogen production costs

Beyond the scope of this chapter, this conclusion highlights the need for a substantial and well-developed analysis of the socioeconomic effects of the hydrogen economy in the MENA region. This type of analysis can determine two factors. The first is how the hydrogen economies of MENA countries can add value to a national economy, for example, in terms of the number of skilled jobs, innovation, investment climate, and end-use customer products. The second is how they can set consistent indicators such as nature conservation areas, primary energy demand, the effects of climate change, emission reduction legislation, and political stability and risk. These unanswered yet essential questions must ultimately be addressed to assess the structural potential of hydrogen in MENA countries.

Europe

In **Chapter 8**, Jan Frederik Braun, Ad van Wijk, and Kirsten Westphal elaborate on the fact that Europe is expected to become a major hydrogen import market in the coming years. The authors explain the main drivers of this development in terms of European countries' ambitions to quickly decarbonize their economies. Such ambitions have been exacerbated by the need to seek energy independence from Russia and their eagerness to create a secure and flexible supply by diversifying energy imports from different regions. Owing to these climate and geopolitical incentives as well as geographical proximity, the Kingdom and other Gulf players now have an additional incentive to position themselves as reliable providers of clean energy imports to Europe. The EU established a Strategic Partnership with the Gulf for stakeholders to develop a shared understanding of value creation, norms, and certification schemes; facilitate the necessary guarantees and funding for the infrastructure; and share knowledge throughout the value chain.

The authors estimate that Saudi Arabia must at least double its goal to 8 million tonnes of exports by 2030 to become a prominent hydrogen-exporting partner for Europe. For this, hydrogen that meets a set of specific sustainability criteria must be produced and the cost of transport and storage facilities must be shared. Europe must quickly develop a coherent import approach that balances renewable and low-carbon hydrogen based on a grounded assessment of production and demand capacities across the continent itself and in the Gulf.

The revitalization of the proposed clean hydrogen-ready Eastern Mediterranean (EastMed) pipeline is a practical example of mutually beneficial cooperation between Europe and Saudi Arabia. The EastMed pipeline has the advantage of complying with the aims and ambitions of the REPowerEU strategy and connecting Saudi Arabia with the European gas grid in a cost-effective manner. It is also important from the vantage point of Saudi Arabia that Europe is a global leader in the patenting and manufacturing of hydrogen technologies throughout the value chain. Exchanging knowledge and transferring technological know-how from Europe to Saudi stakeholders is necessary to support local value creation in end-use sectors and new startup projects in the Kingdom. This could also be crucial for closing the knowledge gap on clean hydrogen between Saudi Arabi and the EU.

In summary, this chapter suggests that the European hydrogen market will not be "up for the taking" by Saudi Arabia. In particular, it will face fierce competition from a range of countries such as Morocco, Tunisia, and Algeria that are geographically closer to Europe. Further, not only can such nations use the existing gas and power infrastructure, but they are also willing and able to supply Europe with vast amounts of hydrogen and its derivatives. Figure 28.2 estimates the hydrogen export capacity of prominent MENA countries that could be connected to Europe via a pipeline.

Finally, another key lesson from the chapter on Saudi stakeholders is that the EU has proactively strengthened the role of the private sector, particularly SMEs, in the hydrogen economy. The EU's flagship hydrogen research and innovation initiative (i.e., the Clean Hydrogen Partnership) has three main objectives. It aims to accelerate the development and deployment of the European value chain for safe and sustainable clean hydrogen technologies; strengthen its competitiveness and support, notably for SMEs; and accelerate the market entry of competitive clean solutions (Hydrogen Europe 2022). Entrepreneurial companies and SMEs are spearheading innovations in hydrogen technology in Europe (Al-Mazeedi et al. 2021). Saudi Arabia must reduce barriers to entry to the extent possible and allow private sector companies, particularly SMEs, to develop or acquire the prerequisite capacity to

- Develop hydrogen and hydrogen-related projects
- Deploy, operate, maintain, adapt, improve, and reproduce the imported hydrogen technologies
- Invent new technologies and commercial solutions

China

Chapter 9 by Tianduo Peng, Xun Xu, Lining Wang, and Jiaquan Dai explains that China deems hydrogen an important building block to meet its climate change mitigation targets. Moreover, it has invested significant technical, financial, and human resources in meeting its ambitions. With its stated goal of achieving carbon neutrality

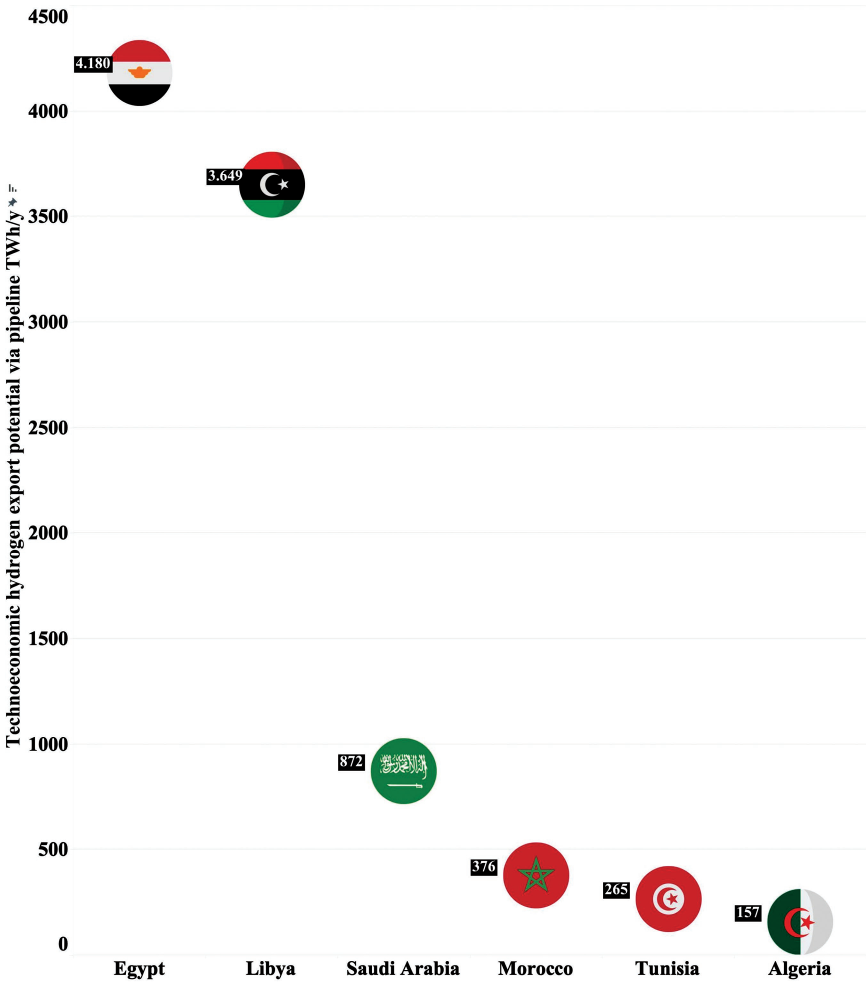

FIGURE 28.2 Technoeconomic hydrogen export potential* via a pipeline (TWh/year) of selected MENA countries.

Source: Authors, based on Braun et al. (2023). *The potential is based on factors such as primary energy demand and production potential. Considering diversification in line with the REPowerEU strategy of possible supplier countries, a minimum export volume to Europe of 55 TWh per selected MENA country is assumed here (or 330 TWh hydrogen/year divided by the six countries).

by 2060 and working toward its carbon emissions peaking by 2030, China's approach to clean hydrogen focuses on three main axes. The first is generating clean energy by expanding renewable energy capacity. The second is expanding CCUS technologies to manage China's current heavy dependence on fossil fuels. The third is providing strong policy support for decarbonizing critical sectors, including the transport, power generation, and steel and chemical industries. China's 2025–2035 hydrogen roadmap focuses on ensuring its continued dominance regarding hydrogen technologies and the associated value and supply chains. Although China is already the world's largest producer and consumer of gray hydrogen, it has recently launched its national emissions trading scheme to incentivize investment in hydrogen and CCUS technologies to further help decarbonize its industrial sectors.

The Chinese approach to hydrogen has concentrated on decarbonizing its domestic industry, with a specific focus on hard-to-abate sectors such as transport and chemicals. China's industrial capacity provides the financial, strategic, and technological leverage to expand its global footprint in a future hydrogen economy. In Saudi Arabia, trade opportunities with China are driven by cross-border investments and joint collaborations on petrochemical, mineral, and hydrogen projects. This was initiated with the signing of a memorandum of understanding during a state visit by Chinese President Xi Jinping in December 2022. This agreement focuses on increasing the two countries' cooperation on hydrogen production. In March 2023, the Saudi Shura Council approved a draft memorandum of understanding between the Ministry of Energy and National Energy Administration of China focusing on the clean hydrogen industry. China's manufacturing capacity, financing capabilities, and construction strength will significantly support the Kingdom's hydrogen ambitions by scaling up electrolyzer, renewable energy, and desalination technologies (Daye 2022).

China's hydrogen value chain development closely tracks that globally and the country is poised to replicate its ongoing success in the solar and wind energy sectors. China has secured technologies to help it achieve self-sufficiency despite repeated attempts by technology-denial regimes (Feng 2023). Its staggering expansion of renewable power (estimated to reach 200 GW of additional capacity in 2023), including the large-scale penetration of electric vehicles across the transport sector, is part of the government's ambition to reduce its dependence on energy imports (Jaffe 2018). This reduced dependence on oil could negatively impact Saudi Arabia, which is among the top suppliers of crude oil to China. However, given that less than 15% of China's oil demand goes toward meeting motor gasoline demand, the impact may not be critical (Cahill, Mazzocco and Huang 2023). China's growing expertise in the electric vehicle space offers it an opportunity to extend trade relationships. This is reflected in the plethora of investments in electric vehicles and technology agreements signed during the 10th Arab China Business Conference in June 2023 (Arab News 2023).

China's ability to scale manufacture and implement policies and technologies to achieve massive cost efficiency has already been proven in the renewable energy field. The country's ambition to export hydrogen as a fuel remains comparatively muted. However, an increase in domestic hydrogen value chain-related manufacturing capacity could easily enable it to replicate its current global dominance in solar panels and wind and enter the future market for clean energy products and technologies. China's manufacturing capacity for electrolyzers and its dominance in the solar panel value and supply chains, coupled with its industrial and technological strengths, indicate its latent aptitude.

United States

Chapter 10 by Naomi Boness and Gireesh Shrimali points out that the US hydrogen strategy, in line with Saudi Arabia's CCE framework, adopts a technology-agnostic approach. The US strategy revolves around three primary priorities:

- Identifying strategic high-impact use cases for hydrogen
- Reducing the cost of hydrogen to $1/kg by 2031 ($2/kg by 2026)
- Developing regional networks (hydrogen hubs)

The strategy relates to two important legislations: the *Infrastructure Investment and Jobs Act* enacted by the Biden administration in 2021 and the *Inflation Reduction Act* signed into law in late 2022. Combined, these legislative acts provide a suite of incentives and grants to encourage hydrogen production and uptake in the United States. Under the *Inflation Reduction Act*, qualifying hydrogen production facilities can obtain a 10-year production tax credit of up to $3/kg. This is likely to make the United States one of the most competitive clean hydrogen producers globally. A major lesson from the US approach is that a clear and focused government-driven incentive or financial mechanism is crucial for attracting industries and investments and retaining talent along the hydrogen value chain, both domestically and internationally. An opportunity for the Kingdom from the development in the United States is that scaling up hydrogen value chains (including CCUS technologies) could have spillover benefits in terms of technological development and cost reductions.

The US hydrogen strategy largely focuses on stimulating domestic markets, achieving self-sufficiency, and meeting the country's national climate goals. However, the incentives under the *Inflation Reduction Act* provide a lucrative opportunity to produce large volumes of clean hydrogen to meet domestic needs and be priced competitively in export markets. Such measures would thus place the United States in direct competition with other exporters, including Saudi Arabia.

Australia

Bart Kolodziejczyk mentions in **Chapter 11** that Australia is well placed to play a significant role in the global hydrogen industry for several reasons. These reasons include: owing to its renewable energy potential, the availability of space to support renewable electricity generation, fossil fuel resources, and stable geology to enable carbon capture and storage. These factors, combined with fossil fuel-based hydrogen production, provide cost-effective options for long-term hydrogen storage (Ellis 2023).

Australia was an early mover in the hydrogen space. It released its national hydrogen strategy in 2019 and has proposed a substantial number of projects. Together with leveraging its vast renewable energy resources, this early start has enabled Australia to pioneer the development of a domestic hydrogen industry; it has also helped the country decarbonize its industrial sectors and strengthen its competitive positioning in exporting commodities and minerals globally and its geographic proximity to key markets in northeast Asia. Its ability to scale projects, coupled with its stated ambition of being one of the largest exporters of hydrogen globally, makes it a major competitor to the Kingdom's hydrogen export ambitions. Australia's established trade relationships with markets in Asia and Europe allow it to position itself as a trusted supplier of energy resources, ensuring offtake possibilities for its low-carbon hydrogen commodities in markets as far away as Europe.

Kolodziejczyk mentions that Australia has a comparative advantage because of its proximity to possible future importers such as Japan and South Korea based on its past coal and mineral exports to these countries. The pilot shipment of hydrogen from Australia to Japan using a purpose-built hydrogen shipping vessel indicates that hydrogen could play an important role in Australia's commodity export portfolio to Japan. However, this will require many more trials to further validate and support the evolving business case. The massive investment by Japan in developing and supporting the hydrogen supply chain (e.g., building hydrogen carriers for marine transport) points toward the inherent attractiveness of the hydrogen import market. However, Australia offers an opportunity to leverage its mineral wealth and extensive mining industry to expand and deepen the Saudi mining sector (Arab News 2021). As the Kingdom continues to invest in the mineral sector overseas, Australia offers excellent prospects for mineral resources (Hook, Dempsey and Al Atrush 2023). The global development of the nascent hydrogen economy could thus enhance new trade relations and develop commercial partnerships that leverage the strengths of the two nations (Cutler 2023). However, Australia risks falling behind countries implementing market-based policy mechanisms and new economic incentives to propel their hydrogen industries, especially the United States (Australian Government 2023). Hence, while Australia is advancing the development of its local hydrogen industry, it remains important to check how its progress compares with that of other nations.

Japan, association of Southeast Asian Nations, and India

Chapter 12 by Yoshiaki Shibata, Victor Nian, Amit Bhandari, and Jitendra Roychoudhury focuses on the hydrogen economies in India, Japan, and the Association of Southeast Asian Nations (ASEAN) countries. The authors describe that Japan's 2014 Strategic Road Map for Hydrogen and Fuel Cells helped pioneer its global focus on hydrogen. This imperative was partly driven by the fact that Japan, which depends heavily on fossil fuel imports, faced challenges in decarbonizing its power generation after its nuclear power plants were shut down due to the 2011 Great East Japan Earthquake. The authors state that, since then, Japan has focused on establishing large-scale global hydrogen supply chains to meet its decarbonization aspirations and energy security needs, primarily in the transport and power sectors.

Japan has leveraged its specific RDD&I strategies undertaken in the mid-2000s, helping it transition from the pilot stage to full-scale commercialization. Further, it has developed a dual approach toward the hydrogen economy. On the one hand, it is decarbonizing its industrial sector to develop the domestic hydrogen economy. On the other hand, it is promoting its proprietary hydrogen production technology to potential hydrogen-exporting countries to develop global hydrogen supply chains. Japan is dependent on hydrogen imports given the scarcity of domestic renewable resources. Hence, the country has created a substantial number of international hydrogen supply chains through collaborations to ensure its energy security. Through pilot shipments from Brunei, the UAE, Saudi Arabia, and Australia, Japan has tried to ensure that it can seed technology and help finance the global development of hydrogen export hubs. Moreover, through the development of a dual strategy of technology push and market pull, it is positioning itself as a key player in both the technology know-how for hydrogen production and transport and the development of a domestic hydrogen market.

Japan's hydrogen technology collaborations with ASEAN countries, specifically Brunei, Singapore, Indonesia, and Malaysia, have enabled it to initiate technology-sharing partnerships. It has thereby gained valuable skills and knowledge while being assured of access to a potential export market. Its long-term associations in this region have resulted in extensive commercial and technical relationships. For example, to ensure a global hydrogen supply, Japan piloted a hydrogen project in Brunei using its proprietary technology to produce and transport hydrogen. Such technical and commercial investments highlight Japan's critical need to diversify its sources of hydrogen production globally.

India is aspiring to become a global hydrogen exporter; however, its domestic market and decarbonization requirements might leave little surplus for exports. Both ASEAN and India have sought to benefit from Japan's technology transfer and learn from its hydrogen experience. Similarly, Japan has forged partnerships with the Kingdom at the government level. This aids the joint development of pilots, which enables stakeholders to understand the complexities of developing markets.

The development of hydrogen markets in this region is important for Japan, as can be observed through the initiation and launch of the Asia Energy Transition Initiative in 2021. This initiative, which focuses on ASEAN members and India and is targeting achieving net-zero emissions, includes financial support of $10 billion for renewable energy projects. Through the Asian Zero Emission Community, Japan has pledged to help Asian economies to decarbonize and support the development of CCUS projects in the region, along with cooperation on hydrogen. These initiatives could challenge Saudi Arabia's position as the leading supplier of hydrogen regionally. It would thus be prudent for Saudi Arabia to expand and develop investment projects that focus on green hydrogen production in the region. The Kingdom's engagement with the PTT Group of Thailand to develop a green hydrogen project with ACWA Power and Aramco could be a template for further exploration. For Saudi Arabia, Japan represents a key future hydrogen export market that has focused on engaging collaborative ventures across organizations. As the hydrogen market develops, increasingly common commercial interests in trade, regional technology-sharing networks, and the enablement of financing will help the development of commercial hydrogen exports within these countries; this will be facilitated by regional cooperation among stakeholders.

South Korea

In **Chapter 13**, Jinsok Sung and Zlata Sergeeva explain that the South Korean government's hydrogen policy focuses on incorporating hydrogen into all sectors of the economy. It also focusses on conducting technological development through drivers such as decarbonizing industry and diversifying energy imports. South Korea is geologically unsuitable for CCUS, and land restrictions will prevent the production of sufficient electricity from renewable sources. As establishing a clean hydrogen industry will be impossible, industrial powerhouses will need to rely heavily on imports. Therefore, South Korea is considered to be a promising market for Saudi Arabia and other countries capable of providing blue and green hydrogen and ammonia, particularly after 2030.

The world's first pilot shipment of certified clean ammonia from Saudi Arabia to South Korea points toward the potentially important role that hydrogen could play in future trade relations between the countries. However, additional pilots and certification to support the evolving structural validity of the business case would help build scale and shape the market.

South Korea, in the development of its domestic hydrogen market, focuses on hydrogen vehicles using fuel cell options. It is seeking to ensure that while it imports hydrogen, it also has suitable export product offerings to take commercial advantage of the energy transition. With its export-oriented economy, South Korea will seek reciprocal business opportunities to trade in technological applications for potential hydrogen imports. This presents an opportunity for the Kingdom; it can leverage not only its low-carbon hydrogen export options with South Korea but also its domestic market access to increase its market share in the South Korean hydrogen import market. South Korea can also use its carbon hub facility to ensure that it can sequester carbon. Increased commercial cooperation along with these energy trade options should provide multiple business opportunities for both countries to leverage the gains from the energy transition by exploiting their individual strengths.

A major challenge mentioned by the authors is that Korean companies lack the technologies to produce green and blue hydrogen in large quantities as well as hydrogen storage and transportation technologies. Moreover, applying hydrogen-related technologies and implementing the relevant infrastructure will require (multi-)billion dollar investments. While this poses a challenge to South Korea, it could provide another area of collaboration with Saudi Arabia.

Russia

Similar to Saudi Arabia, Russia's low-cost resource base coupled with its geographical proximity to markets in Europe and Asia make it highly suitable (on paper) as a major clean hydrogen producer. In **Chapter 14**, Yuri Melnikov describes how Russia has a long history and vast experience with hydrogen dating back to the Second World War. Its experience was enhanced with the implementation of its Space Program and expansion of its petrochemical industry. The existing natural gas infrastructure and pipeline connectivity to Europe and northeast Asia also provide an opportunity to repurpose pipelines and trade routes for exporting hydrogen. Initially, Russia's hydrogen strategy set an annual export target of 2 million tonnes by 2035. The beginning of the Russia–Ukraine conflict in early 2022 quickly decimated Russia's hydrogen export opportunity to Europe. In addition, the conflict has caused a huge exodus of high-skilled workers. This has further undermined Russia's ability to gain a competitive foothold in the innovation-driven and end-use segments of the hydrogen economy, as described in the Introduction.

However, even before the conflict, Russia's policies and regulatory frameworks were inadequate for incentivizing clean hydrogen production and demand, let alone RDD&I. Its initial policies mentioned in this chapter aimed at encouraging clean hydrogen development to diversify exports and identify the limited potential for local end users. In short, the author points out that these initial policies merely provided an unclear framework and did not specify targeted measures. Given the uncertainty of Russia's trade relations with major importers, domestic policies aimed at hydrogen and decarbonization are likely to stall until the conflict is resolved. In this context, there are limited areas for Saudi Arabia and Russia to cooperate, particularly in creating natural gas-based pathways of clean hydrogen such as blue and turquoise hydrogen and developing CCUS technologies. With Russia isolated from the European energy market, it allows Saudi Arabia (and other potential exporters) to potentially capture market shares in Europe and parts of Asia.

Part 3: The clean hydrogen economy and Saudi Arabia: Hydrogen Technologies

The main question for this part of the book was

- **How can the technological gaps in the commercial-scale penetration of clean hydrogen in Saudi Arabia be bridged by targeted RDD&I?**

The challenges and opportunities regarding clean hydrogen for Saudi Arabia from Part 3 are summarized in Table 28.3.

According to World Bank data, Saudi Arabia's R&D expenditure as a percentage of GDP was only 0.5% in 2020 compared with the global average of 2.6%. The United States and Japan's R&D expenditure to GDP ratios are among the highest in the world, at 3.5% and 3.3%, respectively (Heney and Studt 2021). Part 3 points

TABLE 28.3 Opportunities and challenges in hydrogen RDD&I for Saudi Arabia

Opportunities	Addressing research gaps and understanding scaling constraints can help find the right technological blend for decarbonization, supported by evolving policies and regulatory assistance. The ongoing drive toward a knowledge economy can greatly benefit the RDD&I infrastructure and talent building needed to develop the hydrogen economy
	Balancing technology importation and homegrown development, focusing on high-value R&D, and leveraging the role of technical institutions and policy in accelerating hydrogen technology deployment and applications. Saudi Arabia can leapfrog other nations by building a new infrastructure with disruptive technologies suitable to its climate and technoeconomic preferences
	The adoption of hydrogen in many end-use applications can benefit from Saudi Arabia's traditional strength in certain industrial sectors (e.g., oil and gas, steel, cement, mining) and bridge the gaps in other sectors through collaboration with global companies (e.g., scaling green hydrogen production, mobility, heavy duty transport)
Challenges	Understanding that hydrogen growth depends on technological breakthroughs in production, storage, transmission, and infrastructure for cost-effective and reliable use at scale. The RDD&I ecosystem applicable to the hydrogen value chain is at an early stage of development
	Determining the technology readiness levels of critical technologies and identifying promising disruptive technologies suitable for deployment in Saudi Arabia. The legacy of the oil economy warrants selecting technological paths for the energy transition that are conducive for minimizing stranded assets
	Identifying concrete hydrogen utilization areas in various industries and ensuring that technological roadmaps for implementation align with hydrogen availability, transport, and storage infrastructure targets

out that Saudi Arabia's focus on R&D is a central necessity, as this will allow it to achieve its long-term socioeconomic goals and build a knowledge-based economy. This will allow the Kingdom to develop the capacity to produce high-quality, cost-competitive, and innovative hydrogen equipment and components throughout the hydrogen value chain.

The Kingdom recently established the Research, Development, and Innovation Authority, targeting a gross domestic expenditure on R&D of 2.5% by 2040 and planning to create human resources to support this objective (SPA 2022). The goal is to enable Saudi Arabia to become a research, development, and innovation powerhouse and bring its universities and research entities on par with the best in the world. Collaboration and cofunding with research entities, global companies, non-profit organizations, private companies, and startups will be prioritized. The strategy sets ambitious but tangible goals that include taking the country's global competitive index from the 24th position (2022) to the top 10 and including five of its universities into the international top 200. Increasing the number of public–private partnerships, building an extensive talent pool, and creating high-value jobs in science and technology are parts of the Research, Development, and Innovation Authority's plan.

A central message of Part 3 is that an RDD&I roadmap that guides the implementation of essential technologies at the required scale and appropriate cost is needed to establish a world-class innovation ecosystem in Saudi Arabia. This roadmap will be essential for policymakers and research institutions in the Kingdom to direct funding toward focused research areas and infrastructure. Much of the technology infrastructure that Saudi stakeholders from government, industry, and academia will need to build in the near to mid-term should be able to serve its functions for a very long time or be repurposed. This should minimize the potential of stranded assets in the future. Figure 28.3 shows the four pillars of the hydrogen infrastructure and technology pathways in Saudi Arabia.

Based on the four pillars shown in Figure 28.3, Part 3 proposes an RDD&I action plan and a roadmap for hydrogen-specific technologies. A hydrogen technology roadmap is invariably a subset of the broader innovation ecosystem plan of the Kingdom. This ecosystem must adapt innovations from external sources to local priorities and recipient ecologies and create adaptable and original homegrown R&D innovations when external methods are inadequate (Bizri 2018).

Considering that not all technologies require domestic development, the book classifies the relevant technologies into four categories:

- Basic research
- Corporate research and technology translation
- Technology acquisition
- Technology licensing or transfer

These categories, presented in Annex 1, are related to technological maturity, institutional type, national strategic thrust, public/private funding, international collaboration, and technology transfers. The main message of the RDD&I action plan

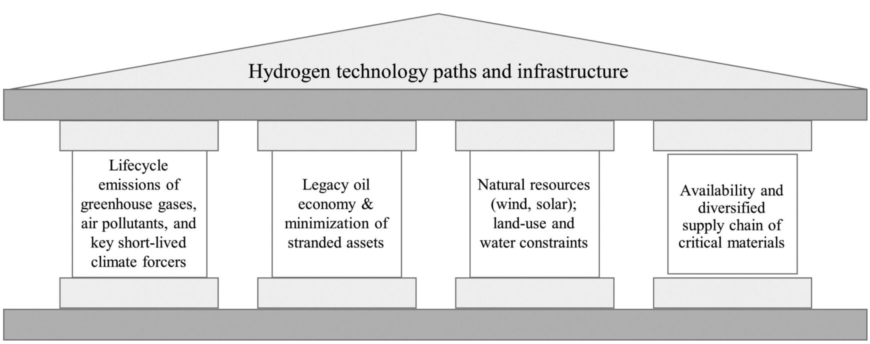

FIGURE 28.3 The pillars of the hydrogen infrastructure and technology pathways.

Source: Authors.

and roadmap is to identify and bridge technological gaps in the commercial-scale penetration of clean hydrogen in Saudi Arabia, which forms the central question for Part 3. The technology roadmap must be aligned with the Kingdom's climate and air quality goals because the infrastructure built today must last throughout the energy transition period and beyond.

In **Chapter 15**, Saumitra Saxena and William Roberts review the current scientific knowledge and understanding of climate change and air pollution. The authors examine how hydrogen can play an indispensable role in achieving the aspirational climate goals in the Paris Agreement. This review, which focuses on Saudi Arabia and its neighbors, summarizes the scientific issues regarding climate concerns. It also recommends the development of technological and policy roadmaps for the hydrogen economy. The main message of the review is that Saudi Arabia's climate policy must incorporate a reduction in significant anthropogenic short-lived climate forcers (SLCFs) such as PM, NOx, and SOx emissions caused by burning fossil fuels.

This chapter further points out that the potential impact of implementing a large-scale hydrogen infrastructure on climate is unknown. There is apprehension about hydrogen leaks from its value chain advancing climate change, while quantifying the impact of SLCF (pollutant) emissions entails uncertainties. Countries have built data inventories for greenhouse gases such as CO_2 and methane from various sources, industries, and sectors; however, such data on SLCFs are unavailable. Precise measurements and estimates of SLCFs and leaks of molecular hydrogen emissions throughout the hydrogen value chain are critical for quantifying their effects on climate change and air quality.

Based on this observation, the authors provide several recommendations:

- Synchronizing the CCE with air pollution control policies
- Building inventories of SLCF emission data from existing fossil fuel-based industries to comprehensively quantify their climate and air quality impacts
- Preparing technology landscapes and hydrogen infrastructure paths based on future hydrogen penetration, the impact on air pollution, and potential leak assessments

The hydrogen technology roadmap can then be synchronized with the CCE and air pollution control roadmaps. Figure 28.4 illustrates the framework for simultaneously addressing climate change and air pollution.

Over recent decades, Saudi Arabia has built an oil and gas infrastructure worth trillions of dollars. Transitioning to a hydrogen economy would result in a massive infrastructural shift. To replace 5 million barrels/day of crude oil (5% of global demand) with hydrogen from water electrolysis, approximately $1 trillion of capital expenditure is required without storage costs (Idriss 2020). One crucial point is that hydrogen uses an infrastructure similar to that of the natural gas industry. The infrastructure built for natural gas, such as storage, liquefaction, regasification,

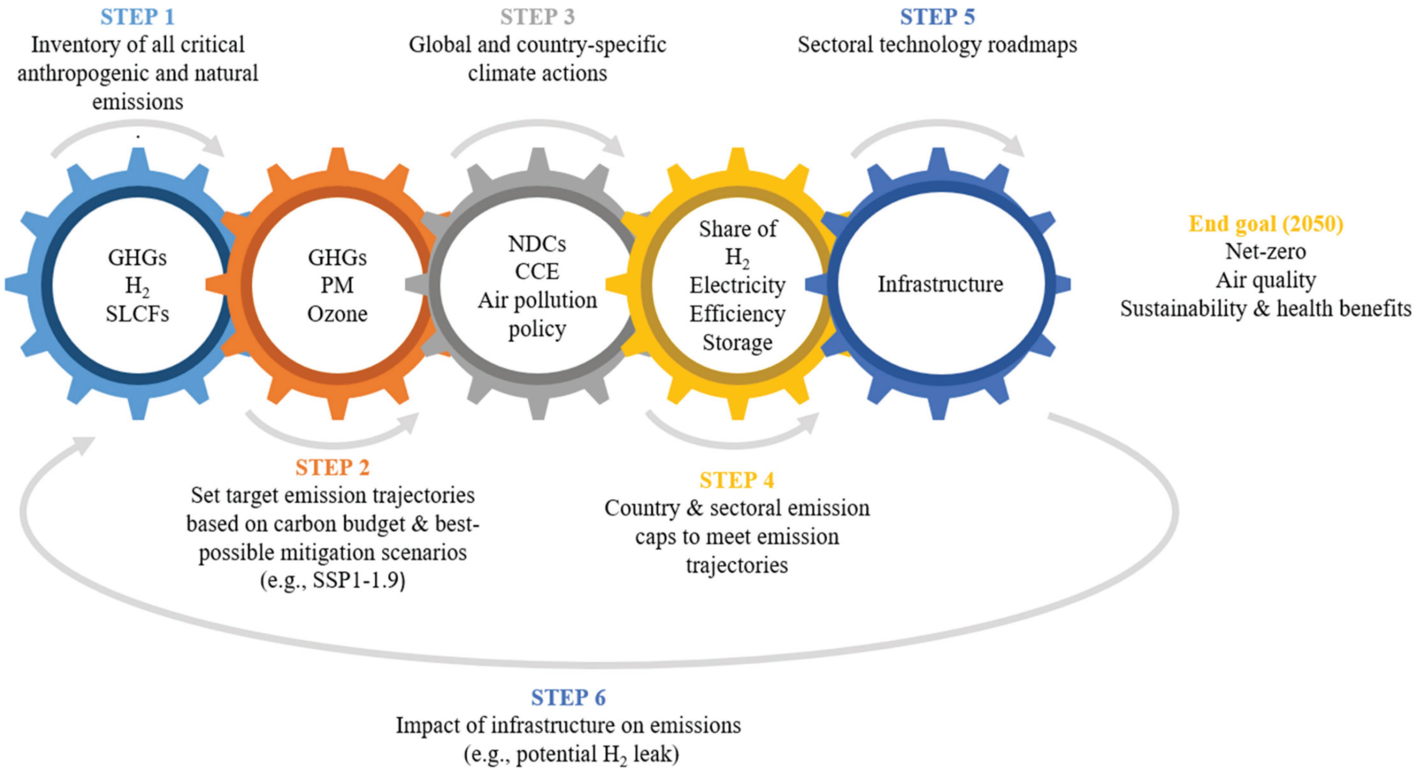

FIGURE 28.4 Comprehensive climate change mitigation and air quality improvements. The supportive role of hydrogen in achieving climate, air quality, and health goals is highlighted. A large-scale hydrogen infrastructure may cause hydrogen emissions. Hence, a feedback loop to an emissions inventory is provided to underscore that possibility. GHG: greenhouse gas, PM: particulate matter, NDC: nationally determined contribution, SSP: shared socioeconomic pathway.

Source: Saxena and Roberts (Chapter 15).

transportation in gas pipelines, and gas distribution, can thus be repurposed for hydrogen. The authors believe that the choice between green and blue hydrogen is complex and regionally dependent. This choice rests on countries' access to natural resources and technologies, energy security goals, and accessibility of affordable energy. The authors emphasize that if hydrogen remains low-carbon throughout its value chain on a lifecycle basis, either the green or the blue route, or a reasonable proportion of both, should be considered. Nonetheless, the green-to-blue hydrogen ratio determines the relevant technological paths in different sectors of the economy. Hence, all technological options for fossil and non-fossil fuel-based renewable energy warrant full consideration.

Figure 28.5 summarizes all the major hydrogen production technologies and corresponding infrastructure paths discussed in Section 3. The main message is that blue hydrogen from natural gas and green hydrogen from renewables will constitute the Kingdom's hydrogen foray into the future; meanwhile, other pathways such as the gasification of petroleum residues, municipal solid waste, biomass, and nuclear energy are also seen as potentially important routes.

Alexander John Cruz states in **Chapter 16** that several crosscutting technologies are common to all infrastructural choices, including water desalination, renewables, power grid stabilization, advanced material recycling, end-of-life technologies, and digital transformation. Electricity grids worldwide require baseload synchronous power, which is typically supplied by fossil fuels, hydropower, and nuclear power. Hence, because of the high variability and intermittency of renewables, global energy systems will continue to seek baseload power from traditional sources until storage technologies (e.g., batteries) improve markedly (by one to two orders of magnitude). Innovation throughout the hydrogen value chain should also focus on the digital transformation through artificial intelligence, Industry 4.0, design and manufacturing, and other enabling and emerging technologies.

In **Chapter 17**, Michelle Schoonover, Mustafa Alkhabbaz, and Mark D'Agostini discuss that it is imperative for blue hydrogen to have low-carbon intensity and minimum fugitive methane emissions. Hence, a high carbon capture (above 90%) is indispensable for making this option sustainable and comparable to green hydrogen. According to the authors, autothermal reforming and the partial oxidation of hydrocarbon feedstock are promising technologies that are rapidly maturing. This chapter states that autothermal reforming and partial oxidation should be preferred over new installations of steam methane reformers with carbon capture and storage or retrofitting old steam methane reformers in Saudi Arabia. Investing in reducing oil and gas carbon intensity and the efficiency of processes and applications could enable a faster and more pragmatic path toward achieving the energy transition in oil-rich countries.

Erika Niino-Esser, Malcolm Cook, Ralph Kleinschmidt, and Tarek El Hawary from thyssenkrupp explore the advancement of gigawatt-scale electrolysis and integration of desalination with offshore wind energy to enhance the flexible

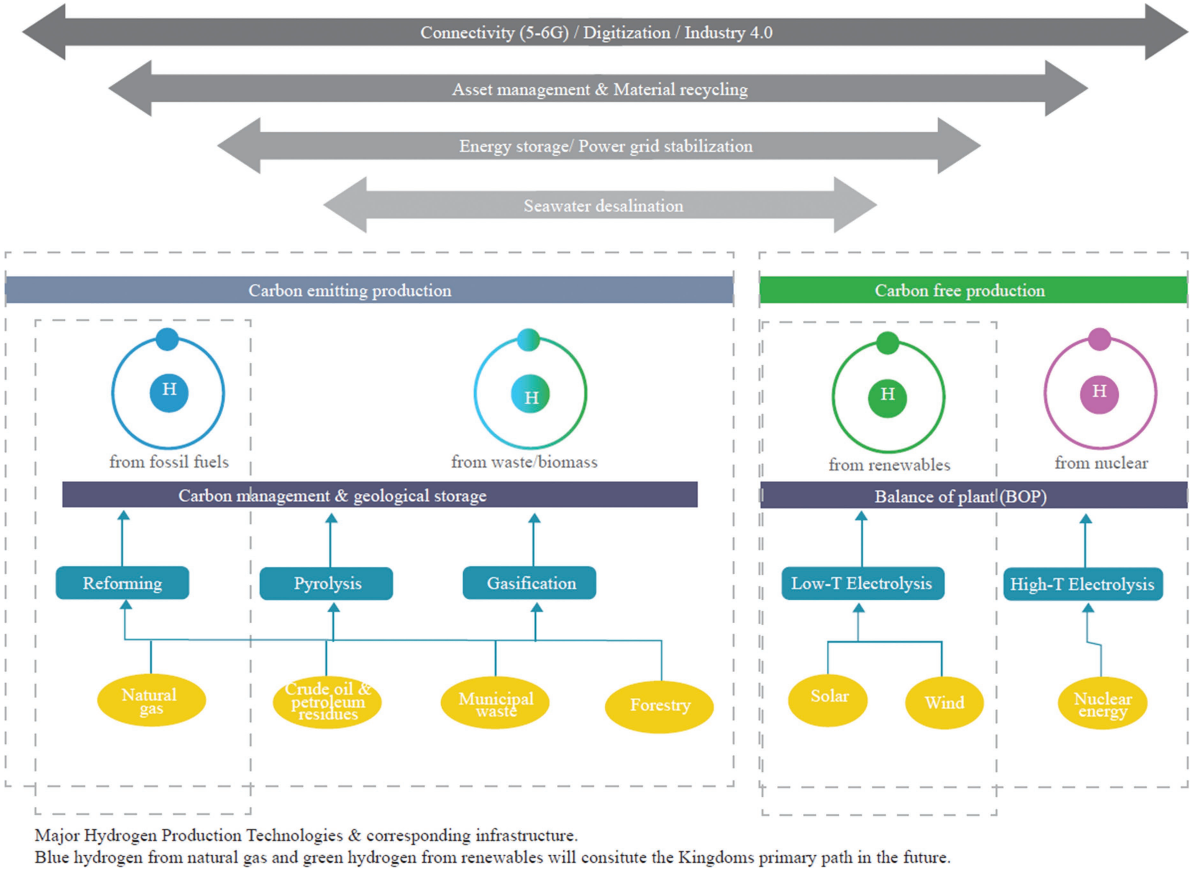

FIGURE 28.5 Major hydrogen production technologies and corresponding infrastructure paths seen as potentially important routes for Saudi Arabia.

Source: Authors.

production capacity for environment-friendly seawater desalination (**Chapter 18**). With a focus on efficiency, scalability, and environmental sustainability, they highlight the immense potential of gigawatt-scale electrolysis to revolutionize hydrogen production. The authors shed light on the latest breakthroughs in seawater electrolysis and offer valuable insights into advancements in this field. By harnessing the vast energy resources offered by offshore wind farms, this innovative approach provides flexible and environmentally friendly desalination solutions. Furthermore, the researchers explore the commercial developments surrounding directly reduced iron, a groundbreaking technology aimed at greening the steel industry.

In Chapter 19, Deoras Prabhudharwadkar, William L. Roberts, Robert Dibble, and Larry Baxter state that the large-scale use of CCUS is critical for preventing large-scale stranded assets in oil and gas. However, the authors discuss that steam methane reformers with carbon capture and storage have been scarcely implemented. The currently used carbon capture and storage with amines has high costs and energy penalties. Moreover, it cannot be suitable for criteria pollutants such as SOx, PM, and NOx. Hence, as an important technological innovation, cryogenic carbon capture is being piloted in the Kingdom; this can reduce the cost and energy penalty of carbon capture and may reduce the emissions of criteria pollutants.

Chapter 20, by Hussein Hoteit and Abdulkader Afifi, points out that the large-scale geological storage of CO_2 and hydrogen is another crucial aspect of infrastructure building. Saudi Arabia has excellent geological locations for both CO_2 and hydrogen storage; however, the storage capacity and associated costs at the country level are unassessed. Assessing the total storage capacity, including characterizing the region, is essential. In addition, the infrastructural requirements, challenges, and potential mitigation measures for geological storage (e.g., leakage avoidance) must be analyzed. Safety considerations for geological storage operations are also important. Permanent CO_2 storage in deep-subsurface formations is technology-ready and scalable (Vahrenkamp et al. 2021). The energy industry has extensive experience in natural gas storage and less experience in CO_2 sequestration, whereas the experience in underground hydrogen storage is limited. Hydrogen storage mechanisms, including secure compression, injection, and withdrawal, are not fundamentally different from those of natural gas. However, the unique thermodynamic properties of hydrogen, its embrittlement to metals, and its reactivity with pore fluids and rocks make hydrogen storage in porous sedimentary rocks underground technically more challenging than natural gas storage. Deep geological formations, including salt domes, saline aquifers, and depleted hydrocarbon reservoirs, can provide safe, reliable, and cost-effective large-scale stores of compressed hydrogen. Hydrogen storage in salt caverns is a mature technology that has been used for decades in various places. By contrast, hydrogen injection and storage in porous formations have yet to be demonstrated on a commercial scale.

In **Chapter 21,** Shashank S. Nagaraj and S. Mani Sarathy discuss the development of e-fuels derived from green hydrogen and carbon capture and storage. They explore their role in energy storage and power-to-X to offset renewable energy intermittency. The heavy-duty transport, aviation, and long-haul maritime sectors are difficult to electrify using current technologies. Hydrogen is an alternative; however, the infrastructure and technologies required for its use as a fuel are immature. In this chapter, the authors explore the distinct advantages of Saudi Arabia in green hydrogen production. They delve into the technologies required to convert hydrogen into e-fuels, which can leverage existing propulsion technologies and fueling infrastructures. Moreover, this chapter examines pilot plants producing green hydrogen and converting it into environmentally friendly fuels such as methanol and ammonia globally. These real-world examples serve as a source of inspiration and illustrate the potential of Saudi Arabia to emerge as a net exporter of green hydrogen and e-fuels.

In **Chapter 22,** Bassam Dally investigates the potential and challenges of hydrogen use in heavy industries in Saudi Arabia, including iron, steel, cement, aluminum, and phosphate. He considers various technologies and strategies for short-, medium-, and long-term implementation. By 2030, small-scale hydrogen blending research and demonstration are suggested to enable integration into existing systems, mainly in the steel, aluminum, and fertilizer industries. This approach requires financial incentives such as carbon taxes and subsidies. Remote power generation offers additional opportunities for the use of hydrogen. By 2040, as low-carbon metal demand and the hydrogen infrastructure grow, industries must adapt. Iron and steel will need modifications for hydrogen use and the role of hydrogen in energy storage and remote mobility is expected to expand. More R&D investment is required for further decarbonization. By 2050, an increased hydrogen supply will improve viability across industries. Further, mature hydrogen technology is widely used for heat generation and mineral reduction. Hydrogen and ammonia will become common backup power sources and green chemicals such as methanol and aviation fuels may become financially viable. R&D focuses on one-step iron reduction, metal recycling, and innovative processes to replace fossil fuels.

In **Chapter 23**, James Turner, Sebastian Verhelst, and Manuel Echeverri Marquez emphasize that hydrogen combustion engines have significant potential and could play an essential role in the future technology mix of carbon-free transportation. This chapter examines the various aspects of hydrogen fuel and its interactions with heavy-duty engines. This highlights the fact that the in-vehicle efficiencies of hydrogen combustion engines can surpass those of proton exchange membrane fuel cells using direct injection fuel systems. However, further research is needed to minimize fuel consumption penalties and protect the components from high temperatures. Alternative engine types such as Wankel engines and two-stroke cycles with opposed-piston architectures may offer improved efficiencies when combined with hydrogen combustion. The hybrid solid oxide fuel cell/gas turbine system is another promising alternative that could be significantly more efficient than both proton exchange membrane fuel cells and optimized heavy-duty engines.

Despite challenges such as long startup times, its potential efficiencies (65%–70% or higher) make it worth pursuing for applications such as large ships, aviation, and stationary power generation. Addressing research and technology gaps is crucial for realizing this potential.

In **Chapter 24**, KACST's Naif Alqahtani and colleagues summarize research on disruptive technologies related to hydrogen production. As a key scientific organization in Saudi Arabia, KACST plays a vital role in developing the nation's hydrogen energy value chain by focusing on clean hydrogen production and utilization. KACST has been active in the hydrogen industry since the 1990s, exploring innovative production technologies for generating carbon-free or low-carbon hydrogen from fossil fuels. These methods include the plasma reforming of natural gas and catalytic microwave pyrolysis of various hydrocarbons. In addition, KACST creates efficient and low-cost catalysts for hydrogen production through water electrolysis, involving the synthesis of catalyst alloys with non-noble metals or low amounts of noble metals. It has also developed solar-driven photoelectrochemical water-splitting processes. In collaboration with various stakeholders, KACST has proposed a comprehensive strategic innovation program to address the R&D gaps in clean hydrogen production and utilization. In addition to renewable-based and natural gas-based options, hydrogen with nuclear energy is a clean option. However, from an infrastructure standpoint, it is a high-cost option in which policymakers and stakeholders would need to invest substantial capital.

Chapter 25 by Sharaf Al Sharif, Saleh Al Harbi, and Abdulrahem Al Judaibi discusses the use of nuclear energy for hydrogen production and the nuclear reactor technologies that can be integrated with hydrogen production facilities. Saudi Arabia plans to build two large nuclear power plants to diversify its energy mix and achieve carbon neutrality by 2060. Nuclear energy is considered to be a clean energy source that may play a crucial role in clean hydrogen production in Saudi Arabia. While current nuclear reactor technologies can produce hydrogen, their costs are higher than those of alternative clean energy sources such as wind and solar energy. Advanced nuclear reactors with improved efficiency and economics are being developed. Clean hydrogen production alternatives such as thermochemical cycling and electrolysis require high temperatures for efficient production. Advanced nuclear reactors can operate at temperatures up to 1000°C, enhancing the efficiency of steam electrolysis and enabling most thermochemical processes. The challenge lies in developing and commercializing high-temperature reactors by 2030, with electrical heating as a potential near-term solution. Depending on the reactor technology, nuclear energy can produce hydrogen at an estimated cost of $2.20/kg.

In **Chapter 26**, Omar Behar, Saumitra Saxena, Deoras Prabhudharwadkar, Bassam Dally, and William L. Roberts provide a technoeconomic analysis of the production, transportation, and cracking of green ammonia. They conclude that significant R&D is required to make green ammonia production and cracking competitive with that of brown or gray ammonia. Reducing electrolyzers' capital expenditure and energy consumption could significantly lower the levelized cost of ammonia. The development of more efficient crackers would improve hydrogen recovery and reduce costs. Additionally, if Saudi Arabia aims to export green ammonia, local production technologies must be enhanced, and cracking technologies could be developed in partnership with ammonia-importing countries.

Saudi Arabia has ample natural resources such as wind, solar, and land to build a self-sufficient hydrogen economy. However, water is scarce in the Kingdom. While the water–energy nexus is a worldwide challenge, this problem has critical dimensions for severely arid and water-stressed countries such as Saudi Arabia. Indeed, the potential for hydrogen production via green and blue pathways is tied to the availability of desalinated water and its carbon intensity.

In **Chapter 27**, Friedrich Alt and Christopher M. Fellows propose that the deployment of technologies that reduce water desalination needs and energy intensity is crucial to Saudi Arabia's hydrogen ambitions. The authors discuss the water requirements for producing green hydrogen in Saudi Arabia and make several crucial points. One is that water demand for electrolysis is approximately 10–15 m^3 of desalinated water per tonne of hydrogen. This corresponds to a required desalination plant capacity of 60,000–90,000 m^3/day for a target green hydrogen capacity of 2 million tonnes. Importantly, for green hydrogen production, a high-purity distillate that can be produced by thermal desalination plants may be advantageous over the drinking water produced by seawater reverse osmosis (SWRO) plants. This is because water quality influences the water demand, energy consumption, and efficiency of a green hydrogen production plant. Water consumption during hydrogen production may be limited to about 10 kg of high-purity distillate per kg of hydrogen. By contrast, it may be up to 50% higher when using drinking water of the quality produced by SWRO plants or typical tap water. Drinking water would require additional pretreatment upstream of hydrogen production, which must be noted when considering the overall power consumption and capital cost of the hydrogen production process. In comparison with the total water consumption in Saudi Arabia, desalinated water demand for green hydrogen production would be 0.50%–0.75%. The desalination water capacity for green hydrogen production would be approximately 0.7%–1.1% of Saudi Arabia's future full desalination plant capacities. This additional increase was estimated by the authors based on the prevalence of SWRO in the future. Comparing the allocatable average CO_2 emissions of future desalination systems with hydrogen production by electrolysis operating with electric power generated by fossil fuels, the contribution of CO_2 emissions from the desalination process to hydrogen production would be below 0.1%. This is equal to the range of 0.01–0.04 kg CO_2/kg water.

According to this analysis, the water requirements and associated carbon intensity for producing hydrogen in the Kingdom appear high but manageable. Saudi Arabia should consider renewable desalination and brine treatment technologies to meet hydrogen demand. The estimates can vary, but the underlying high water demand needs remain unchanged. Although the direct electrolysis of seawater is at a low technology readiness level, its potential for Saudi Arabia is encouraging because its energy intensity is very high.

Challenges for the hydrogen economy: the evolving criticality of minerals and technologies

Beyond the scope of the chapters covered in Part 3, the energy transition is significantly mineral intensive, and some of the production and processing of these minerals are geographically concentrated. Clean hydrogen pathways are no exception. An increase in manufacturing demand as economies recover from the impacts of COVID-19 and supply chain disruptions has raised the prices of minerals and metals needed in significant quantities to achieve net-zero emissions. According to the International Energy Agency, to reach the 2°C scenario under the Paris Agreement, demand for minerals should quadruple by 2040 (IEA 2021). Achieving net-zero by 2050 requires a six-fold increase in minerals by 2040. The International Monetary Fund's *Energy Transition Metals Index* shows a significant jump in prices, particularly after the recovery from the COVID-19 lockdown, as illustrated in Figure 28.6.[3]

The increase in metal and mineral prices can impact the speed of the deployment of low-carbon technologies and slow the transition to net zero. Figure 28.7 shows the metal and mineral requirements of electrolyzers and fuel cells, which rely heavily on nickel, zirconium, and platinum-group metals.

To build the giga-scale electrolyzers required for clean hydrogen to play a critical role, a significant number of precious metals are required. For example, catalysts for proton electrolyte membrane electrolyzers comprise platinum-group metals (typically 65% iridium and 35% platinum), and iridium is considered to

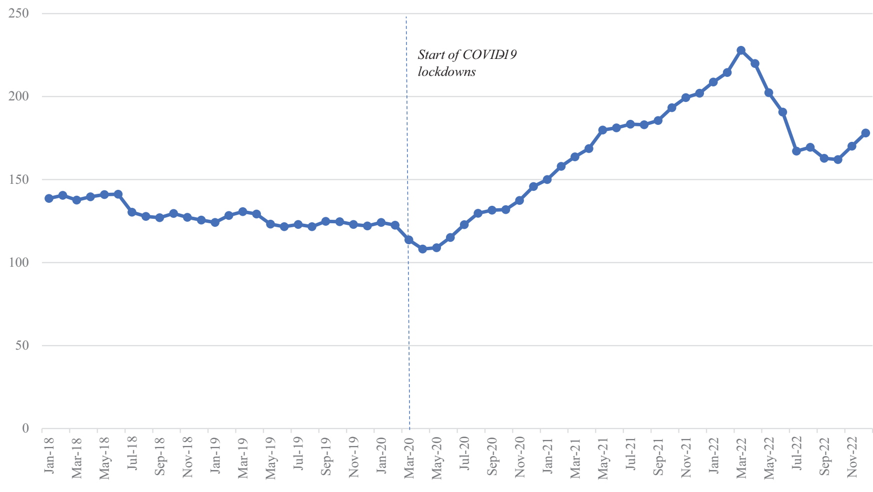

FIGURE 28.6 Energy Transition Metals Price Index (2016 = 100).

Source: International Monetary Fund (2023).

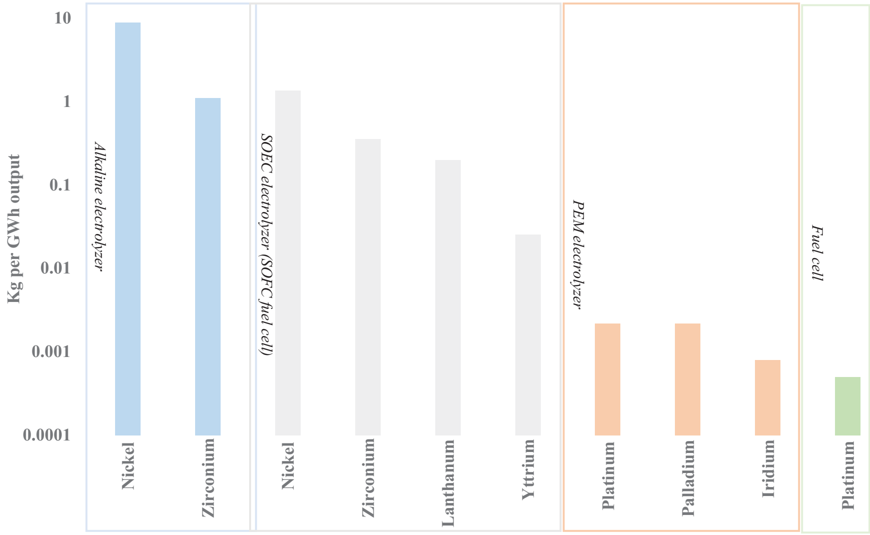

FIGURE 28.7 Estimated mineral demand in electrolyzers and fuel cells (log scale). Note: SOEC: solid oxide electrolyzer cell, SOFC: solid oxide fuel cell, PEM: proton exchange membrane.

Source: IEA (2021).

be one of the scarcest elements on earth. Iridium is also produced as a byproduct of platinum and palladium production and its reserves are concentrated in South Africa, which holds 91% of global reserves (Crooks 2022). The vulnerabilities of the hydrogen supply chain are further amplified when considering the metals and minerals required to create renewable energy capacity and transmission lines required to power electrolyzers. Improving the efficiency of catalysts and materials could reduce the number of metals and minerals required. However, this also highlights the importance of diversifying clean hydrogen production pathways such as blue hydrogen to lessen the burden on precious metals and mitigate further cost increases.

Saudi Arabia is taking the necessary steps to enhance the resilience of its critical mineral supply chains. The Kingdom is scaling up domestic mining and securing critical international mineral supply chains. Saudi Arabia's mining company, Ma'aden, launched a mining fund with the PIF, with investments reaching $15 billion to secure access to minerals such as copper, nickel, and lithium (Hook, Dempsey and Al-Atrush 2023). In addition, processing these minerals is energy-intensive, and the Kingdom is well positioned to process these minerals domestically, given its low-priced energy and electricity. The development of electrolyzer technologies and need to rebuild electrolyzers to cope with the degradation and refurbishment opportunities from spent fuel cells offer the Kingdom the opportunity to establish a domestic manufacturing and recycling sector for critical minerals. It has already set up a catalyst manufacturing factory, with SABIC announcing a strategic project to ensure that Saudi Arabia is self-sufficient in catalysts for the oil and gas sector. This is helping pave the way for the Kingdom to become a future manufacturing hub for specialized minerals (SABIC 2023).

To conclude, the growth in the clean hydrogen economy over the coming decades must be considered in synergy with electricity, as the former complements the latter in the global energy transition. This means that hydrogen has a range of potential applications in sectors in which electrification is either too costly or impossible. Although this book focuses on clean hydrogen, it recognizes that this molecule is not the only solution to climate change and will have to compete with other decarbonization solutions in each sector. Saudi Arabia is well positioned to become a global producer, consumer, and exporter of clean hydrogen and its derivatives in an increasingly carbon-constrained world. However, this book points out that Saudi Arabia is set to compete on a playing field that is different from that defined by its ability to produce, trade, and set production limits for fossil fuels in the global market. The Kingdom will need to quickly develop an innovative and competitive ability to capture value along the supply chain of an international clean hydrogen economy.

In the context of net-zero ambitions and within a rapidly diminishing timeframe for halting global climate change, this book considers hydrogen technology options using fossil or non-fossil fuel-based renewable energy. It also points out that while the development of a clean hydrogen economy represents a massive commercial opportunity, it also requires elaborate cooperation among stakeholders from the government, industry, and academia. Innovative technology solutions that will help support and sustain the development of this market will increasingly require supportive business models that can meet the many specific challenges that clean hydrogen poses. While incentives and a supportive regulatory environment will help foster development, it is imperative that a market develops so that subsequent projects can be financed with lower borrowing costs. This will enable the massive scaling up of production, thereby helping define clean hydrogen in the forthcoming decades.

Annex 1

Table 28.1A presents a roadmap for hydrogen technology development in the Kingdom, with the selected research areas or technologies chosen from the contributions to Part 3 of the book. This list of technologies is representative, if not exhaustive. Table 28.1A considers two time horizons: from now to 2030 and from 2030 to 2050. These horizons are referred to as the short- and long-term horizons,

TABLE 28.1A Hydrogen RDD&I action plan and roadmap

Column 1	*Column 2*	*Column 3*	*Column 4*	*Column 5*
Technology maturity (2022)	Concept development TRL ≤ 4	Small and large prototypes: Startups: 4 ≤ TRL ≤ 6	Startups, large demonstration; Novel technologies: 6 ≤ TRL ≤ 9	Deployment; Mature technologies: 8 ≤ TRL ≤ 11
Activity	Basic research	Technology development, translation, and firm research	Technology acquisition and collaboration	Technology transfer and licensing
RDD&I action	Build strategic institutions and develop human capital; increase international research collaborations in hydrogen-specific and overlapping fields	Enhance academic to industry research translation; conduct objective-based research in industrial labs	Acquire technology companies owning niche technologies by domestic entities and joint ventures	Perform technology licensing from global companies to domestic entities; technologies are mature and do not require domestic development
Desired outcome	Fundamental research in scientific and engineering disciplines; scouting potential innovative solutions/ concepts and technologies; preparing an educated and skilled workforce	Prepilot scale demonstration; component performance assessment; seeking industrial partners for technology deployment	Pilot-scale demonstration with industrial partners supported by venture capital; risk retirements; system performance assessment	Business contracts and offtake agreements, plant setup, and commissioning; supply chains; economies of scale
Funding source	Public funds; university endowments	Public/Private collaboration	National companies/ venture capital investments, sovereign wealth funds (Taqnia); corporate venturing (e.g., Aramco, NEOM, Abdulateef Jamil)	Private/National company partnerships
Time for commercial adaptation	5–20 years	3–5 years	2–3 years	<2 years

(Continued)

TABLE 28.1A (Continued)

Column 1	*Column 2*	*Column 3*	*Column 4*	*Column 5*
Examples	Hydrogen/NH_3 combustion; steam calcination PV; sour gas cracking	Ammonia cracking; DAC (Aramco–KAUST collaboration)	Acquiring companies in the league of Monolith and Proton Energy	Jizan IGCC and NEOM
Short-term critical (<10 years): criticality increases from left to right	Membranes; catalysts electrochemistry, materials water splitting, photoelectrochemical water splitting, plasma advanced nuclear reactors/cycles; hydrogen from sour gas; hydrogen/NH_3 combustion; hydrogen steam calcination	NG pyrolysis; DAC; cryogenic carbon capture; hydrogen storage in salt caverns; synthetic fuels; hydrogen/NH_3 for ICEs; waste-to-hydrogen pathways	Advanced PV and batteries; PEM; ATR and partial oxidation+CCS; nuclear hydrogen; hydrogen pipelines; hydrogen in gas turbines; hydrogen in DRI; power-to-X technologies; waste-to-hydrogen; NH_3/methanol marine fuels; Fischer Tropsch synthesis fuels (eKerosene); AI, connectivity; digitalization	Steam methane reforming+CCS retrofit; amine-based CCS; geological storage of CO_2; GW-scale AWE; petroleum residue gasification+CCS; FCEVs; fuel-switching liquid to NG/hydrogen in power generation
Long-term critical (>10 years): criticality decreases from left to right	Basic research on novel technologies unknown today	Mining for critical minerals	Alternative materials	TW scale solar/wind-driven electrolysis
		Renewable desalination	Flexible and hybrid renewables	Mature hydrogen/CO_2 storage and utilization
		Hardware manufacturing	AEM, solid oxide fuel cells	Grid stabilization
		Heavy industry applications	GW-scale nuclear H_2	
		Hydrogen and synthetic fuels for aviation	CSP driven electrolysis	
		Hydrogen fuel cells for shipping	Large-scale DAC	
			Direct NH_3 gas turbines/fuel cells	

Note: Examples of national companies include Aramco, SABIC, Ma'aden, and the Saline Water Conversion Corporation. Private sector companies include Air Products, Baker Hughes, ThyssenKrupp, and ACWA Power. TRL: Technology readiness level, AWE: alkaline water electrolysis, PEM: polymer exchange membrane electrolysis, AEM: anion exchange membrane, SOEC: solid oxide electrolyzer cell, NG: natural gas, ATR: autothermal reforming, DAC: direct air capture, CCS: carbon capture and storage, FCEV: fuel cell electric vehicle, ICE: internal combustion engine, DRI: direct reduced iron steel, PV: solar photovoltaic, CSP: concentrated solar power, AI: artificial intelligence, GW: gigawatt, TW: terawatt, NH_3: ammonia. *Source:* Authors.

respectively. Public spending on R&D increases from right to left, while technological maturity increases from left to right. In other words, areas of basic research today (column 2) will gradually move from yellow (column 3) to blue (column 4), and finally to green (column 5) and will become the mature technologies of the future. Green blocks consist of fully commercial technologies that will lead to infrastructural growth on an industrial scale.

Notes

1 Guarding interoperability implies, among other factors, setting up an independent tracking standard that sets common rules for governance, implementation, and quality control. It also implies an independent and local issuer that implements the hydrogen code in each country of operation (backed by the internationally accredited code and tracking standard).
2 In the book and claim tracking system, the physical delivery of the energy carrier and issuance of the certificate can be traded separately. In the mass balance model, the energy carrier and certificate are linked along the chain of custody.
3 The International Monetary Fund's *Energy Transition Metals Index* includes the prices of aluminum, chromium, cobalt, copper, lead, lithium, manganese, molybdenum, nickel, palladium, platinum, rare earth elements, silicon, silver, vanadium, and zinc.

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