Dominik Möst · Steffi Schreiber ·
Andrea Herbst · Martin Jakob ·
Angelo Martino · Witold-Roger Poganietz
Editors

The Future European Energy System

Renewable Energy, Flexibility Options and Technological Progress

REflex
Analysis of the
European Energy System

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Foreword

The transition to a climate-neutral energy system in 2050, largely based on renewable energy sources, can be seen as a technological rupture vis a vis the still largely fossil fuel-based energy and economic system in place. It is a source of challenges and opportunities for economic actors, in the EU and globally. Research and innovation will play a crucial role to accompany the transformation be it through individual technology development, or systemic innovation. The key to success in the long-term is to develop a wide portfolio of cost-effective and efficient carbon-free alternatives, in combination with solutions for an integrated energy system, built on digitalization and sector integration.

It will be essential to plan and operate such a system "as a whole," across multiple energy carriers, infrastructures, and consumption sectors, by creating stronger links between them with the objective of delivering low-carbon, reliable, and resource-efficient energy services, at the least possible cost for society. The recently published EU strategies on Energy System Integration[1] and on Hydrogen[2] look into an efficient integration of decarbonized, mostly renewable, supply of electricity.

As the name of the present EU project, REFLEX, indicates, exploring sources of flexibility, on various time scales, between different geographical locations and different sectors will have to play a key role in an energy system with a very high share of renewable and increasingly dispersed energy sources. Energy storage, including the production of hydrogen and e-fuels emerges as a key enabling technology for addressing these flexibility requirements and for providing green electricity for electrified transport, industry, and buildings sectors and thus providing further rationale and helping the sectoral integration.

Understanding this complex transition of the energy system and its components requires a sound methodology that can capture the dynamics within different fields and the interplay between these. Given the 2050 time horizon considered for reaching climate neutrality, the interaction between technology development and energy system design becomes crucial. While many technologies required for the

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[1] COM (2020) 299—Powering a climate-neutral economy: An EU Strategy for Energy System Integration, Brussels.

[2] COM (2020) 301—A hydrogen strategy for a climate-neutral Europe, Brussels.

energy transition are known in principle, costs may change rapidly as seen for renewable energy during the last decade. Research and innovation will define the speed at which the decarbonization can take place and at which costs.

Mathematical models have been one key tool, supporting energy policy for many years and they are constantly improving often supported by projects like REFLEX. Given the complexity of the problem, model coupling becomes an almost natural approach, as there often is no one-size-fits all solution. This can also be observed along the different chapters of this book, which touches subjects such as the dynamics of technology development, the contribution of sector integration to flexibility and design options for electricity markets. While seemingly distinct, these fundamental building blocks and their interrelationships need to be understood in the context of the energy transition. It is thanks to projects like REFLEX that we have gained decisive and important insights into the interplay of sectors and economic actors and that our respective methodologies keep improving.

Brussels, Belgium
August 2020

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Acknowledgments

Writing, coordinating, and editing a book necessitates the engagement of many experts and contributors. First of all, all authors of the book are very grateful for the financial support given by the European Commission. The book is based on analyses and results of the EU project "*REFLEX—Analysis of the European Energy System Under the Aspects of Flexibility and Technological Progress*," which received funding from the European Union's Horizon 2020 research and innovation program [GA-No. 691685]. Further information related to the REFLEX project is published on the website http://reflex-project.eu/.

The authors of the book thank the European Commission for funding and supporting the project from April 2016 to April 2019. In addition to the financial support, the following experts from the European Commission were personally dedicated to the project and supported us with their helpful comments: Andreas Zucker supported the project by regularly attending REFLEX events, and by giving presentations as well as helpful suggestions, especially for the results evaluation. Patrick van Hove discussed very interested and appreciative the outcomes and supported the project constructively during its whole duration. Manuela Conconi, being responsible as project officer, was very helpful and constructive, gave detailed feedback to milestones and reports and was always available to support our project.

Furthermore, we want to thank the members of the REFLEX External Advisory Board for their willingness to participate and their suggestions during the project period.

In addition, we appreciated the comprehensive exchange within workshops organized by the European Commission with the projects SET-Nav, MEDEAS, and REEEM, which were projects funded within the same call of the European Union's Horizon 2020 research and innovation program. Thanks goes to the coordinators of these three projects for the constructive exchange, namely: Gustav Resch, Jordi Solé Ollé, and Mark Howells.

Many thanks to the keynote speakers of the final REFLEX workshop for sharing their insights and contributing to the results discussion, in particular Katrin Schweren and Thierry Coosemans.

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Finally, the editors of the book are very thankful to all authors for their engaged efforts to make the book a success, even beyond the project duration.

Dominik Möst
On behalf of all editors

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Part I
Introduction, Scenario Description and Model Coupling Approach

Chapter 1
Introduction

Dominik Möst, Steffi Schreiber, and Martin Jakob

Abstract The future energy system in Europe needs to be decarbonized and thus be based almost exclusively on renewable energy sources. Therefore it is challenged by the intermittent nature of renewables and requires several flexibility options. The interaction between different options and the impact on environment and society are in the focus of this contribution. It is the core objective of this book to analyze and evaluate the development toward a low-carbon energy system with focus on flexibility options in the EU to support the implementation of the Strategy Energy Technology Plan. The analyses are based on a bottom-up modeling environment that considers current and future energy technologies, policy measures and their impact on environment and society while considering technological learning of low-carbon and flexibility technologies.

The reduction of greenhouse gas emissions is one of the main challenges that the European Union is facing in the coming years and decades. Achieving the targeted emission reductions requires a fundamental transformation of the energy sector. Responding to the Paris Agreement the European Green Deal sets the overarching aim of making Europe the first climate neutral continent by 2050 and includes a set of policy initiatives by the European Commission.[1] Until 2030, EU's greenhouse gas emissions should be reduced to at least 55% compared with 1990 levels.

The EU's energy legislation as well as the EU's energy technology and innovation strategy (Strategy Energy Technology Plan—SET), aim at creating an framework

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[1] The European Green Deal is a concept presented by the European Commission in December 2019. First legislative initiatives e.g. for higher fossil fuel prices and stricter CO_2 regulations are available by mid of 2020.

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conditions that facilitate the evolution of existing as well as developing new low-carbon technologies that can cope with the specific needs for a stable, cost-efficient and sustainable prospective energy supply. Moreover, these legislative initiative and strategy promote in particular the deployment of renewable energy sources (RES), the electrification of demand side sectors and improved energy efficiency in the electricity, heat and transport sector. In addition, these measures are framed by additional roadmaps that trigger investments in the development of complementary technologies for energy conversion (electricity and heat provision), transportation and consumption (mobility, buildings, industry, and transport), such as power-to-x technologies, grid infrastructure, and demand side management.

Yet, several technologies, which will play a crucial role in next decades in the EU strategy, challenge the energy system by their intermittent nature. The two most abundant forms of power on earth are solar and wind. Both have been and will be becoming more cost–competitive compared to other energy carriers for electricity generation and thus are key factors in achieving climate reduction targets. Yet, the integration of intermittent renewable energy sources necessitates flexibility in the energy system. A large bundle of technologies may provide the needed flexibility such as energy storage systems, smart grids, adaptation of conventional power plant technologies, and demand side management. These applications are often cross-sectoral and can be complemented by power–to–x, such as power-to-heat (e.g., heat pumps, district heating), power-to-transport (e.g., electric mobility, fuel cells), power-to-gas (e.g., H_2, CH_4), power-to-fuels, and power-to-industry (e.g., H_2 for methanol or ammoniac production) for the electrification of other sectors.

It is thus the core objective of this book to analyze and evaluate the development toward a low-carbon energy system with focus on flexibility options including power-to-x options in the EU up to the year 2050 to support a better system integration of renewable energy sources. The analysis and findings in this book are based on the EU-funded project "*REFLEX - Analysis of the European energy system under the aspects of flexibility and technological progress.*" The REFLEX project was embedded in the Horizon 2020 Work Program "Secure, clean and efficient energy" of the EU and addressed the topic LCE-21-2015 "Modelling and analyzing the energy system, its transformation and impacts" during the project duration from May 2016 until April 2019. Thereby nine partners from six European countries contributed with their expertise, especially in energy modeling, to the successful project implementation, in particular: TU Dresden, (Chair of Energy Economics) as coordinator, Energy Systems Analysis Associates—ESA^2 (Dresden), Fraunhofer Institute for Systems and Innovation Research (Karlsruhe), Karlsruhe Institute of Technology (Karlsruhe), Royal Institute of Technology (Stockholm), TEP Energy GmbH (Zurich), TRT Trasporti e Territorio (Milano), University of Science and Technology—AGH (Krakow) and Utrecht University (Utrecht).

New technologies and innovations are necessary to address the scrutinized challenges having the (future) competitiveness of technologies as well as their social impacts in mind. To assess the competitiveness of technologies and their interrelation, the cost effectiveness of the future energy system in a systemic context requires for a well-founded energy system analysis including an evaluation of technological

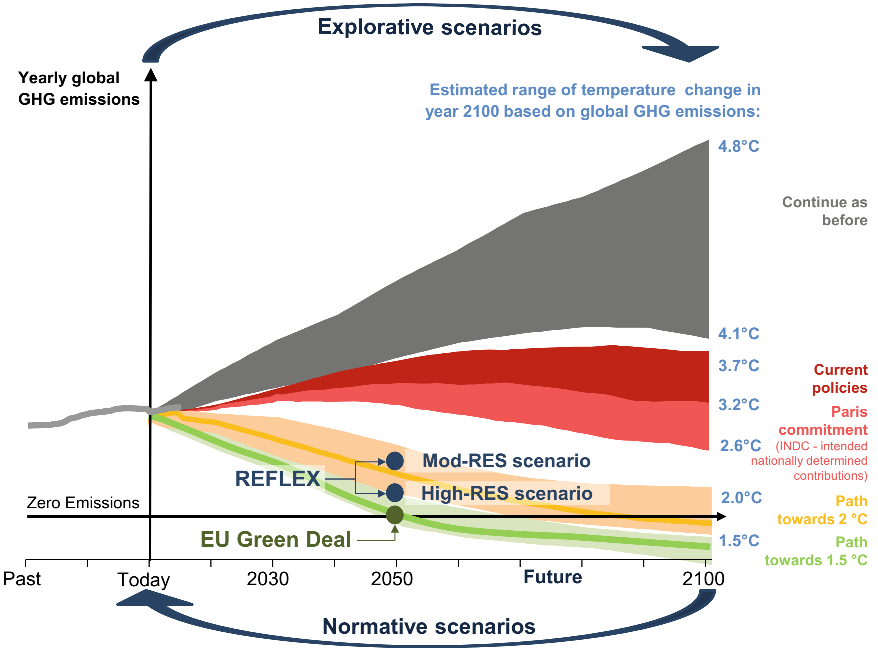

Fig. 1.1 Schematic illustration of REFLEX Mod-RES and High-RES scenarios presented in this book in the context of global greenhouse gas reductions. Own illustration adapted and based on Climate Action Tracker (2018)

learning. Within REFLEX this challenge is addressed by the integration of experience curves as well as socio-economic impact analysis in an integrated energy models system. Hence, the analysis is based on a modeling environment that takes into account the full extent to which current and future energy technologies and policies interfere and how they affect the environment, economy and society while considering technological learning of low-carbon technologies and of applications providing flexibility.

An extensive modeling framework combining the expertise of the nine partners is developed using a quantitative scenario approach as basis of the analysis. Thereby, scenarios describe possible futures by formulating a lot of "if-then" conditions. Scenarios reflect different assumptions about how current trends will unfold, what critical impact factors are and what policymakers should take into consideration. It is important to notice that scenarios are current futures (for decision-making today), but not a future present (in the sense of a forecast). Scenarios may be either normative or explorative (cf. Figure 1.1). Normative scenarios describe what has to be done to achieve a given target or "perfect future." Normative scenarios orient energy policy in terms of what needs to be done today to achieve the targets. Explorative scenarios are from a today's perspective more plausible and challenge the paths toward what seems to be possible to be achieved.

As depicted in Fig. 1.1, two main scenarios are distinguished in the REFLEX project: a reference scenario based on observed trends and a policy scenario representing more ambitious decarbonization pathways for Europe until 2050. The reference scenario is defined as a moderate renewable scenario (Mod-RES) while the ambitious policy scenario is defined as a high renewable scenario (High-RES). A detailed description of the scenario assumptions can be found in following Chapter 2. While both scenarios cannot be clearly grouped in one of the two scenario categories, the Mod-RES scenario is closer to an explorative (in the sense of continuing trends) and High-RES closer to a normative one (in the sense that it is very ambitious and further strong and additional policy measures are needed). Figure 1.1 depicts these two scenarios with regard to the European Green Deal as well as with regard to estimated ranges of global temperature changes.[2] Note that Fig. 1.1 is only a schematic illustration that strongly simplifies the paths related to climate change and should not be misinterpreted: especially, the presented scenarios in this book focus only on Europe, while the indicated paths with regard to temperature changes necessitate global action.

To analyze and evaluate the development toward a low-carbon energy system with focus on flexibility options, REFLEX brings together the comprehensive expertise and competences of known European experts. Each partner focuses on one or two of the research fields: techno-economic learning, fundamental energy system modeling or environmental and social life cycle assessment. To link and apply these three research fields in a compatible way, an innovative and comprehensive energy models system (EMS) is developed, which couples the models, tools, findings and data from all involved partners in this book (cf. Chapter 3). It is based on a common database and scenario framework. The results from the energy models system helps to understand the complex links, interactions and interdependencies between different actors, available technologies and impact of the different interventions on all levels from the individual to the whole energy system. In this way, the knowledge base for decision-making concerning feasibility, effectiveness, costs and impacts of different policy measures is strengthened and shall assist policymakers.

This book describes possible pathways and necessary steps toward a more sustainable energy system based on a detailed and fundamental analysis of the energy system. Derived from the abovementioned core objective, following sub-goals are addressed and structure this book:

1. Analyze and model the impacts of technological development and innovation on the energy system by enhancing and combining different sectoral approaches and experience curves (cf. Part I and II).
2. Set up a holistic and consistent (socio-technical) scenario framework based on the Strategy Energy Technology Plan (SET-Plan) up to the year 2050 (cf. Part I, especially Chapter 2).

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[2] The REFLEX Mod-RES and High-RES scenarios were defined long before the more ambitious European Green Deal policy targets were published. However, the High-RES scenario already anticipated the more ambitious targets and comes close to meeting the European Green Deal.

3. Develop an Energy Models System (EMS), which links different models and approaches, including a common database and interface to analyze the complex interactions and interdependencies between the different actors, the available technologies and the impact of the different interventions on all levels from the individual to the whole energy system (cf. Part I, especially Chapter 3).
4. Derive experience curves for energy technologies and incorporate them in the energy models systems to assess the future competitiveness of upcoming technologies and their diffusion into the system as well as their interferences with existing technologies, including grid aspects (cf. Part II).
5. Comparative assessment of prospective flexibility portfolios to integrate RES-based electricity generation, considering demand side management, grid reinforcement, energy storage, flexible generation capacities, and alternative electricity market designs as well as their impacts. While Part III focuses on demand side flexibility and the impact of disruptive technologies, Part IV has a strong focus on the supply side and system perspective as well as on market design issues.
6. Quantification of external costs and socio-environmental impacts of whole energy system transition pathways, considering the entire life cycle of new and existing energy technologies (cf. Part V).
7. Derive policy measures from the entire assessments in the framework of the SET-Plan to assist policymakers in identifying and analyzing effective strategies for a transition to an efficient low-carbon energy system (cf. Part VI).

Reference

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Chapter 2
Scenario Storyline in Context of Decarbonization Pathways for a Future European Energy System

Andrea Herbst, Steffi Schreiber, Witold-Roger Poganietz, Angelo Martino, and Dominik Möst

Abstract This chapter presents a qualitative description of the scenario storylines for the REFLEX project. The scenario descriptions provide the overall qualitative framework for the modeling activities by setting-up two holistic socio-technical scenarios based on different storylines: the moderate renewable scenario (Mod–RES) as reference scenario and the (de-)centralized high renewable scenarios (High–RES) as ambitious policy scenarios. The chapter highlights the definition of main techno-economic framework parameters, macro-economic and societal drivers as well as of the considered political environment.

2.1 Introduction

Energy systems could be seen as socio-technical systems, i.e., technical change and societal dynamics influence each other. Due to the relevance of societal dynamic values and behavioral patterns, the degree of acceptance and willingness to support technical changes as well as social policies and regulation are equally important for the success of a transformation process, compared to technological or economic

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The content of this chapter is based on the REFLEX project reports from Herbst et al. (2016), Fuss et al. (2018), Zöphel et al. (2019) as well as on the REFLEX policy brief from Poganietz et al. (2017).

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factors (Verbong and Loorbach 2012). Thus, the future design of the European energy system, and by this the most suitable mix of decarbonization technologies and flexibility options, is highly dependent on interdependencies between economic constraints, technology and resource availability, and societal preferences and demands that can change over time. The interrelationships can vary between the member states, increasing the complexity for any widely accepted solution regarding the design of the European energy system. To deal with the complexity and the uncertainties of the transformation process, scenarios are a proven tool to structure and trigger discussions. The aim of the REFLEX scenario definition is to sketch the relevance of the future energy system design for the significance of different flexibility options. To clarify the options, two framework scenarios will be presented which account for socio-economic and socio-political uncertainties.

The structure of this chapter continues with the overall scenario definition and its general drivers in Sect. 2.2. The socio-technical scenario description follows in Sect. 2.3, before a detailed definition of the reference scenario Mod-RES in Sect. 2.4 is provided. Followed by the description of the applied scenario frameworks and policy measures for the ambitious High-RES centralized and decentralized scenario in Sect. 2.5. In Sect. 2.6 concluding remarks are drawn.

2.2 Scenario Definition and General Drivers

The European Green Deal presented by the European Commission in December 2019 has the aim of making Europe the first climate-neutral continent with no net greenhouse gas emissions by 2050 (EC 2020). Furthermore, the European greenhouse gas emission reduction targets for 2030 are increased to at least 50–55% compared to the levels of 1990. Currently, the achievement of these ‘new’ European climate targets are unclear due to the economic and financial crises resulting from the uncertainties of the Covid-19 pandemic. The ambitious scenarios of the REFLEX project show a path between the achievement of the current climate targets and a reference development without additional ambitions (cf. Chapter 1). In the REFLEX project two main scenarios are distinguished: a reference scenario based on observed trends and a policy scenario representing two more ambitious decarbonization pathways for Europe until 2050. The reference scenario is defined as a moderate renewable scenario (Mod–RES) while the ambitious policy scenario can be differentiated between the decentralized versus the centralized high renewable scenario (High–RES). The following Fig. 2.1 illustrates how the REFLEX scenarios can be schematically classified in terms of the existing energy system.

Overall differences occur between the Mod-RES and High-RES scenarios, both at European and country level. The main qualitative definitions of framework conditions and policy targets for the REFLEX scenarios are shown in Fig. 2.2. In both REFLEX scenarios identical GDP and population projections have been chosen as calculation basis to ensure an undistorted analysis of technology impacts, policy options, their interaction and optimal portfolio as well as their impact on environment and society.

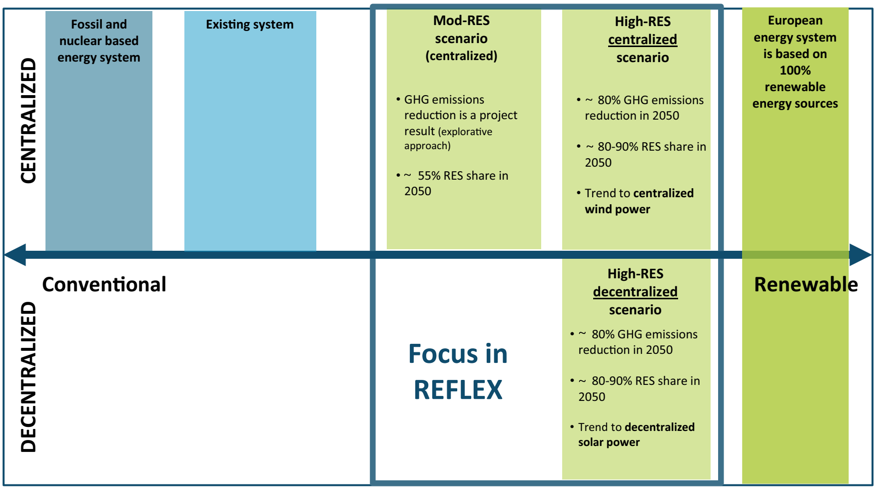

Fig. 2.1 REFLEX scenarios (transition pathways) embedded in a schematic illustration of possible energy systems. The assumed future RES share of the High-RES scenarios should provide 80–90% of today's electricity demand in Europe (~3,000 TWh). Figure according to REFLEX project 2019

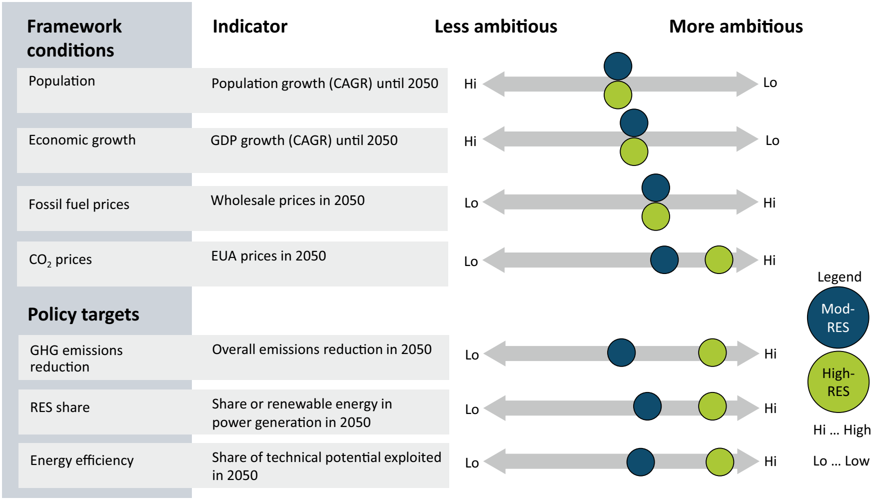

Fig. 2.2 Definition of REFLEX framework conditions Mod-RES compared to High-RES scenarios (Hi = High, Lo = Low). Figure according to REFLEX project 2019

The framework conditions for the *moderate renewable scenario (Mod-RES)* are based on the EU Reference Scenario 2016 (Capros et al. 2016). The Mod-RES scenario is defined to reflect the development of the energy system taking into account past dynamics but also the future developments regarding current economic developments and energy policies.[1] Present policy targets and actions which have been already decided or implemented are reflected in Mod-RES. This is not necessarily the most likely or the most probable future development, but rather serves as a projection to which the policy scenario with ambitious decarbonization pathways is compared to (cf. Figure 2.2).

The framework conditions for the *high renewable scenario (High-RES)* are similar to those of Mod-RES in terms of population and economic growth, while energy prices and CO_2 prices are assumed to be higher. Furthermore, ambitious climate policies are considered in High-RES. One major target of the scenario is to limit global temperature increase to 2°C, by more drastically reducing GHG emissions and achieving the EU 2020 energy saving targets in the short term. Higher contribution from learning curves and need for flexibility options due to a large share of intermittent renewable energy sources occur. To capture the different possible stances on a future energy system without differentiating too much, two versions of the high renewable scenario (High-RES) are developed within REFLEX: the *decentralized* case and the *centralized* case. Major differences of these two cases concern the amount of (de-)centralized technologies. This includes both the demand and supply side in the sectors electricity, heat, and transport. A more detailed distinction follows in Sect. 2.5.

The assumptions regarding general scenario drivers are based on the EU Reference Scenario 2016 provided by the European Commission (Capros et al. 2016) and integrated into the overall REFLEX modeling platform. Common assumptions that are the same for the reference (Mod-RES) and policy (High-RES) scenarios include among others the gross domestic products (GDP), gross value added, number of households, wholesale prices for major energy carriers and population. Assumptions that differ between the scenarios are for instance GHG emission reduction targets, RES shares, energy efficiency measures, vehicle stocks, fuel taxes or CO_2 emission allowance prices, to name few. More information about the scenario-specific assumptions are included in Herbst et al. 2016 and Fuss et al. 2018.

2.3 Socio-Technical Scenario Framework

The aim of the socio-technical scenario descriptions is to provide a qualitative account of the potential future social, economic, political, and technological drivers that are coherent with the REFLEX quantitative scenarios. The scenario descriptions are based on previous work that developed future scenarios (e.g., Watson and Albritton 2001; Bernstein et al. 2008; UNEP 2012; van Vuuren et al. 2012; Pachauri et al. 2014). The REFLEX socio-technical scenarios use the Global Environmental Outlook 4 (GEO-4) scenarios as a starting point. The reasons therefore is that the GEO-4 scenarios were developed in consultation with governments and other organizations

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[1] Cut-off date is the end of 2015.

across the world. Furthermore, the GEO-4 scenarios reflect differences in key drivers that the REFLEX scenarios also aim to reflect. More specific descriptions are shown in the following Table 2.1.

The primary assumption of the Mod-RES scenario is that no policy measures are introduced beyond those that have been decided or already implemented (cut-off date 2015). Therefore the Mod-RES scenario emphasizes the continuation of existing policies on climate change mitigation, innovation, value systems, and economic growth. In particular, the Mod-RES scenario assumes that the current balance between the government and private sector is maintained in the future, and free trade remains a prime goal of international cooperation. The maintenance of the status quo is evidenced in the continued role of private institutions in education, healthcare, and research and development aid. Meanwhile, as a reference scenario, only existing international agreements and policies are in place to mitigate environmental degradation and climate change. Since no new policy measures are assumed, there is a little emphasis in this scenario on social development beyond the status quo either. Public participation in government is relatively low, governmental North-South development assistance is unchanged and no further action is taken to develop cultural understanding and diversity. Markets are open to international trade, and there is little regulation to ensure just employment conditions. Personal values are individually focused and individual resource demands follow historical trends related to economic output. The socio-technical context of Mod-RES is based on the assumptions of the ‘Market First’ scenario in GEO-4 (UNEP 2007).

The High-RES scenario assumes a strong policy commitment to achieve societal goals for climate change mitigation, as well as other social and economic goals. In this scenario global governments become sufficiently aware of the myriad social and environmental challenges facing society to implement policy to yield improvements in these areas. Economic growth is maintained at the same level as in the reference scenario (Mod-RES). However, in the High-RES scenario economic growth is always considered simultaneously with environmental and social impacts. Thus this scenario differs from Mod-RES, in terms of increased role for government in general and cooperation on environmental and social issues. Further, in the High-RES scenario there is increased public spending worldwide on health and education, and growing North-South development aid. In light of this cooperation, international institutions such as the EU and UN increase in importance and new cooperation emerge. Technological innovation still has a strong market focus, though there is a larger role for government engagement. Innovations focus as much on reduction of environmental impact as on economic efficiency. Trade between nations is encouraged, but requirements for fair trade are emphasized. Considering societal values, there is little overt action on the issue of cultural understanding and diversity. However, public participation in governance is generally higher in the High-RES scenario compared to the Mod-RES scenario. Personal values are in general more community-inclined than in Mod-RES scenario, though individual resource demands still follow historical trends related to economic output. The socio-technical context of High-RES is based on the assumptions of the ‘Policy First’ scenario in GEO-4 (UNEP 2007).

Table 2.1 Socio-technical scenario descriptions. As noted driver categories, critical uncertainties and the description of the scenarios themselves are based on UNEP's GEO-4 scenarios from UNEP (2007). Table according to Fuss et al. (2018)

General driver	Critical uncertainty	Presented in scenario		Quantitatively taken by		Model-input parameter
		Mod-RES	*High-RES*	*eLCA*	*sLCA*	
Institutional and socio-political frame-works	General nature and level of par-ticipation in governance	Low, following current trend	Medium		X	Broad differentiation between scenarios affecting e.g., rates of corruption
Demographics	Number of children women want to have when the choice is theirs to make	Trend toward fewer births as income rises	Trend toward fewer births as income rises based on proactive policies		X	Differential evolution of e.g., life expectancy at birth
Economic demand, markets and trade	Actions taken related to the open-ness of mar-kets	Move toward in-creased openness	Openness with some emphasis on fair trade principles		X	Differential improvement of wide range of social parameters between scenarios
Scientific and technological innovation	Emphasis in terms of energy technologies	Technologies developed to improve economic efficiency	Technologies developed to im-prove general efficiency and envi-ronmental impacts	X	X	Techno-eco-nomic parameters (e.g., in-stalled ca-pacity)
	Access and availability of new tech-nologies	Dependent solely on the market		X	X	Evolution of market share
Value systems	Emphasis on individualism related to the community	Individual	Greater emphasis on community		X	Greater tendency for community action, e.g., collective bargaining

2.4 Moderate Renewable Energy Source Scenario (Mod-RES)

The moderate renewable scenario (Mod-RES) considers targets and actions which have been decided or are already implemented at European and national level in 2015. Selected relevant policies in this context are:

- the Renewable Energy Directive (Directive 2009/28/EG; CEU 2008)
- the Energy Efficiency Directive (Directive 2012/27/EU)
- the Directive on Energy Performance of Buildings (Directive 2010/31/EU)
- the Ecodesign Directive (Directive 2009/125/EC)
- the Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles (Directive 2009/30/EC)
- the EU regulation on CO_2 emission from new cars and vans (Regulation (EU) No 333/2014, Regulation (EU) No 253/2014)

In addition, the EU Emissions Trading Scheme and the expected CO_2 emission allowance price trajectory are relevant for industry and the power sector (based on Capros et al. 2016 for the Mod-RES scenario). Furthermore, business-as-usual technological learning is assumed in the Mod-RES scenario. However, progress from learning effects as well as knowledge transfer is less pronounced than in the High-RES scenario. In Table 2.2 the development of current policies in the Mod-RES scenario are described more in detail.

2.5 Centralized versus Decentralized High Renewable Scenario (High-RES)

In the high renewable scenario (High-RES) an overall 80% GHG emissions reduction in 2050 (compared to 1990) is intended, following the ‘Roadmap for moving to a competitive low-carbon economy in 2050’ of the European Commission (COM 2011/0112). In comparison to the existing Roadmap to a low-carbon economy in COM (2011/0112), the High-RES scenario has a special focus on the influence and potential of flexibility mechanisms and learning curve effects of specific technologies (from economies of scale but also from additional investment in R&D and new technologies) in all sectors (e.g., electrolysis in industry or electric vehicle deployment targets in the transport sector). In addition, methanation, water electrolysis for hydrogen production, methanol synthesis, Fischer-Tropsch-synthesis, etc. could be relevant for sector coupling in this context. However, the final composition of flexibility options and additional learning curve effects is identified within the project and is, therefore, more a project result than a scenario assumption.

For the more ambitious High-RES policy scenarios, some measures from the Mod-RES scenario are further intensified and complemented by additional regulations and instruments in order to achieve a stronger shift to more efficient and/or innovative

Table 2.2 Development of current policies[a] in the Mod-RES scenario. Based on the before mentioned legislative directives and on own assumptions. Table according to Herbst et al. (2016)

N°	Measures/Regulations	Legislative	Implementation
1	**Technology standards**	Ecodesign Directive	MEPS for all lots for which regulations have been implemented before 29 February 2016
2	**Energy efficiency standards for renovation**	Directive on the energy performance of buildings	National building code requirements, 2015 or planned tightening as far as data available
3	**Energy efficiency standards new buildings**	Directive on the energy performance of buildings	National implementation of nearly zero-energy building (NZEB) standards after 2018 (for public buildings) and 2020 (for all buildings).
4	**RES obligation**	Renewable energy directive	Current implementation in Member States (only for new buildings in few countries), increased share of biofuels for all transport modes, reduced biofuels taxation for transport use
5	**Energy labeling**	Energy labeling directive	Mandatory for new devices for appliances already included /initiated in 2016
6	**EU Emission Allowances**	Emission Trading Scheme	CO_2 price: increase to ~ 90 EUR/t_{CO2} in 2050 (e.g., from EU Reference Scenario 2016 or model result) Transport sector: increase of cost (e.g., air mode)
7	**Energy and CO_2 taxation**	Energy Taxation Directive	Taxes varying by fuel and sector and by country (e.g., German RES levy)
8	**Energy saving obligation**	Energy Efficiency Directive	Current implementation in Member States 1.0-1.5% p.a.
9	**Fuel Quality**	Fuel Quality Directive	CO_2 emission factor for fuels
10	**Clean and Energy Efficient Road Transport Vehicles**	Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles	Renewal of the road vehicle fleet
11	**CO_2 standard for new cars and vans**	EU regulation on CO_2 emission from new cars and vans	Renewal and technology of cars and vans vehicle fleet

(continued)

Table 2.2 (continued)

N°	Measures/Regulations	Legislative	Implementation
12	**Aviation policies**	Single European Sky II	Air non fuel cost, air access time to airport, air fuel consumption
13	**Aviation policies on emissions**	ICAO Chapters 3 (reduction of noise at source emissions)	Air emission factors
14	**Maritime energy efficiency**	IMO Energy Efficiency Design Index (EEDI)	Reduced ship fuel consumption factor

[a] Cut-off date: end of 2015, MEPS—Minimal Energy Performance Standards, ICAO—International Civil Aviation Organization, IMO—International Maritime Organization

technologies/modes, and to alternative fuels as they summarized in Table 2.3 for the industry and tertiary and residential buildings and appliances as well in Table 2.4 for the transport sector.

2.5.1 Centralized High-RES Scenario

2.5.1.1 Scenario Framework of a 'Centralized World'

The centralized High-RES scenario describes a world, in which the electricity market will be dominated by large scale offshore and onshore wind power plants at prime locations. To realize the advantages of such system, i.e., rather low generation costs and making use of deviating loads between North and South Europe, the required grid infrastructure needs to be integrated. Despite the high share of RES, the scenario would allow for some large scale conventional, low-carbon emitting power plants and nuclear power plants.

The heat production for residential and office buildings is centralized in the cities, equipped with large scale thermal storage charged with power-to-heat technologies, such as heat pumps and electric boilers (cf. Table 2.3). Hydrogen is produced in larger plants with distribution by trailers and pipelines. This leads to higher perceived reliability concerning hydrogen infrastructure deployment and stability of hydrogen prices compared to decentralized world due to less actors and need for coordination combined with clear decisions and communication.

Economies of scale will promote larger capacities of conversion technologies (as long as policy interventions will not encourage investment in small scale technologies), resulting in a more centralized world. But the costs of transporting energy will influence the degree of centralization, i.e., high transport costs could hinder the establishment of a centralized world. Having said that, a 'centralized world' can be characterized by a more market-oriented paradigm, assuming in the scenario that economies of scale will dominate transport costs. The selection of the energy

Table 2.3 Key assumptions and differentiating factors for the High-RES industry, tertiary and residential scenarios. Table according to Zöphel et al. (2019)

Clusters of mitigation options	Mod-RES	High-RES
Industry		
Incremental efficiency improvement	Energy efficiency progress according to current policy framework and historical trends.	Faster diffusion of incremental process improvements (BAT & INNOV $\geq$ TRL 5)[1]
Fundamental processes improvement	–	Radical process changes (INNOV $\geq$ TRL 5)
Fuel switching to RES, decarbonized electricity and hydrogen	Fuel switching driven by energy prices and assumed CO_2 price increase	High financial support for RES technologies (biomass, power-to-heat, power-to-gas) Additional financial support for the use of district heating in the centralized scenario. Radical changes in industrial process technologies drive fuel switch (e.g., switch to hydrogen)
Recycling and re-use	Slow increase in recycling rates based on historical trends	Stronger switch to secondary production
Material efficiency and substitution	Based on historic trends	Increase in material efficiency and substitution
Tertiary and residential buildings & appliances		
Energy efficiency of residential & tertiary buildings **Building standards for new and renovated buildings, compliance**	Current national implementation of regulations (nearly zero-energy buildings from 2021), high compliance	Higher building standards for renovation, very high compliance, financial incentives
Renovation rate	Remains at the current status	Increases by 70% (up to 2%) until 2050
Heating supply in buildings **Technology choice, lifetime**	Implemented national incentives and subsidies stay in force, no additional fuel tax Average lifetime 20–30 years	Financial incentives for heat pump investments, financial revenue for heat pump flexibility, expansion of district heating networks, ban of oil boilers from 2030, additional tax on gas and oil Average lifetime 20 years
Energy efficiency progress of appliances	Ecodesign directive in today's implementation and further announced reinforcement	Ecodesign directive in today's implementation and further announced reinforcement, plus new efficiency classes and more products from 2025

[1] BAT—best available technology, INNOV—innovation, TRL—technology readiness level

Table 2.4 Key assumptions and differentiating factors for both High-RES transport scenarios. Table according to Zöphel et al. (2019)

<table>
<tr><th colspan="3">Strategies</th><th colspan="2">High-RES</th></tr>
<tr><th>(1)</th><th>(2)</th><th>(3)</th><th>Decentralized</th><th>Centralized</th></tr>
<tr><td>X</td><td></td><td>X</td><td colspan="2">Road infrastructure pricing based on emissions, diffusion of Collaborative Intelligent Transport Systems applications, urban policies to promote sustainable mobility, measures promoting efficiency improvements, and multimodality</td></tr>
<tr><td></td><td>X</td><td></td><td colspan="2">Increased fuel tax for conventional fuels, reduced fuel tax for electricity, hydrogen, and biofuels</td></tr>
<tr><td></td><td>X</td><td>X</td><td colspan="2">Filling and charging station deployment is further expanded, fast charging increases acceptance of BEV and enables driving longer distances</td></tr>
<tr><td></td><td></td><td>X</td><td colspan="2">More ambitious CO_2 standards for new cars and light duty vehicles and extension of standards to buses and trucks</td></tr>
<tr><td>X</td><td></td><td>X</td><td>Higher acceptance of multi-modal transport increases the use of car sharing and leads to more walking and cycling. Car sharing fleets have a higher share of electric vehicles.</td><td></td></tr>
<tr><td></td><td></td><td>X</td><td>Strongly increasing number of households with rooftop PV accelerates the diffusion of electric vehicles due to economic advantages by own electricity production and higher technical affinity</td><td></td></tr>
<tr><td></td><td></td><td>X</td><td>Spillovers from stationary battery storages could accelerate the reduction of battery prices</td><td></td></tr>
<tr><td></td><td>X</td><td>X</td><td colspan="2">FCEV as zero-emission technology choice for intermediate and long-distance trucks, advanced research and innovation for fuel cell technology and decision on deployment of hydrogen refueling infrastructure in all EU-28 countries</td></tr>
<tr><td></td><td>X</td><td></td><td>Hydrogen production directly at the filling stations</td><td>Hydrogen production in larger plants with distribution by trailers and pipelines</td></tr>
<tr><td></td><td>X</td><td>X</td><td></td><td>Higher perceived reliability concerning hydrogen infrastructure deployment and stability of hydrogen prices compared to decentralized world due to less actors and need for coordination combined with clear decisions and communication</td></tr>
</table>

(continued)

Table 2.4 (continued)

Strategies			High-RES	
(1)	(2)	(3)	Decentralized	Centralized
		X	Phase-out of pure ICE vehicles for new urban buses with completion in 2035 and for new cars and light duty vehicles in 2040	

*Impact of the assumptions related to the three main European strategies for the transport sector
(1) Increasing the efficiency of the transport system
(2) Speeding up the deployment of low-emission alternative energy
(3) Moving toward zero-emission vehicles

technologies as well as flexibility options will follow more profit-oriented rules. Current regulations, which support local, non-commercialized energy provision, are not extended. A market-oriented paradigm means also a rather traditional organization of energy markets, i.e., the classical dichotomy of supply and demand will apply; prosumers or non-profit-oriented energy association will not experience a noteworthy share at the electricity market.

A pre-condition for this is a general acceptance of the required infrastructures, e.g., of HVDC lines, or intervention into nature, e.g., to establish wind onshore plants on fallow land, in affected regions. This acceptance could be either the result of appropriate incentive systems, like the possibility to buy shares of the network operators at preferential conditions or the common understanding that the economic advantages of such centralized system outweigh the environmental disadvantages.

The establishment of such an energy system requires corresponding measures by the national governments and the European Commission, following a centralized policy scheme, e.g., directing expansion plans. Limiting appeals by citizen to speed up investment in the grid could be part of such a policy.

2.5.1.2 Flexibility Options in a 'Centralized World'

A characteristic of the 'centralized world' is an intra-European trade of electricity, i.e., excess demand or excess supply in one region can be mostly, if not completely, buffered by other regions. Additionally, respective large storage systems are available for balancing the grid system. More centralized information availability on status and condition of large scale power plants allows for better forecasting of available renewable generation (day ahead). Based on the available and precise information on generation capacity online at every time interval, the need for demand side flexibility is limited. Other central options, e.g., flexible power plants or the use of backup capacity from large storage, would be more cost competitive to balance electricity supply and demand compared to decentralized smaller scale demand side measures which would need to be aggregated to support grid stability.

Therefore, in the tertiary sector, only very limited appliances and technologies (energy services) with a large electricity demand would be effectively used for demand side measures such as cold storage houses, large night storage heater or heat pumps, and large ventilation, and air-conditioning systems. As of today, these large energy services make up only a small share of the electricity demand from the tertiary sector in Europe, whereas only a fraction of this demand is theoretical available for demand side management (DSM) measures. In a 'centralized world,' this very limited flexibility potential would be considered as stable. Depending on the country regulation for participation in the balancing market, this DSM potential is already tapped as of today. These DSM options would be centrally controlled and marketed on balancing markets where grid operators are solely responsible for requesting the needed DSM capacities.

Transport and power-to-x technologies could be additional flexibility options. Whether power–to–x technologies will play an important role, depends on the abundance of off-peak electricity, next to technical restrictions, like flexibility of downstream technologies and low energy efficiency in case of re-electrification. The revenues from selling off-peak stored electricity have to match the high annualized investment and operating costs, at least. The abundance of off-peak electricity in a 'centralized world' may be low, if the abovementioned flexibility options will be successfully applied. Flexibility options within the mobility sectors will mainly occur with the diffusion of electric mobility.

2.5.2 Decentralized High-RES Scenario

2.5.2.1 Scenario Framework of a 'Decentralized World'

In contrast to the 'centralized world,' the decentralized High-RES scenario characterizes an electricity market which will be dominated by rooftop PV plants and wind onshore power plants at all possible locations, amended by further local based energy technologies, like small scale biomass power plants. A consequence should be a diminishing relevance of intra-European trade of electricity. Large conventional power plants will be rather negligible. The residential heat production is backed by solar systems and small scale storage systems. Through the following three factors a faster diffusion of electric vehicles is expected in the High-RES decentralized scenario compared to the centralized scenario. First, the strongly increasing number of households with rooftop PV accelerates the diffusion of electric vehicles. Second, battery prices decline faster due to additional learning curve effects based on spillovers from stationary battery storages leading to lower selling prices of BEVs and PHEVs. Third, people are more familiar with DSM and digitalized monitoring and control, and thus a higher acceptance of multi-modal transport is assumed including more use of car sharing as well as more walking and cycling. This behavior change increases the number of vehicles in car sharing fleets that tend to have a higher share of electric vehicles. Furthermore, the hydrogen production for the demand side is decentralized and directly located at the filling stations and industrial production sites.

A ‘decentralized world’ implies that non-efficiency oriented factors are gaining influence in the shaping of the future energy system. A main driving force for many advocates is the conviction that only grassroot movements could secure the energy transition toward RES and would impede a non-sustainable energy system (cf. Viardot et al. 2013). The local or regional energy systems (including local infrastructure) have to be owned and controlled by local groups or local residents to secure among other a fairer distribution of wealth by breaking up the market power of large utilities. However, the REFLEX decentralized High-RES scenario will allow for profit-oriented companies as market participants. Although in such a world, profit-orientation will not be the dominant motivation for providing energy, the operator will organize the energy system still cost-efficiently. A ‘decentralized world’ could also be a consequence of a deep-rooted opposition in affected regions against new HV or HVDC lines, which cannot be overcome by policies. A pre-condition for a ‘decentralized world’ is a general acceptance of relevant power and heat energy conversion technologies either in the neighborhood or in the buildings. This could mean to some extent intervention into nature, e.g., to establish decentralized wind power plants. This acceptance could be either the results of appropriate incentive systems, like the possibility to participate at the profits of energy sale, or by reduced tariffs. The establishment of such an energy system requires corresponding measures by the national governments and the European Commission. But in contrast to the ‘centralized world,’ these measures will set only a broad legal and economic frame for establishing local groups, like local energy associations and has to be amended by regional or local directives and pushed by local groups. The transformation is more a bottom-up process.

A pre-condition for both scenarios is the switch of the current energy system to smart(er) grids, smart metering, and smart appliances and thus, acceptance by the user for those technologies (cf. Verbong et al. 2013). The demands for smart systems will differ between both scenario worlds, since the requirements regarding the control systems and the combination of flexibility options are influenced by the ‘(de-)centralization’ grade of the energy system.

2.5.2.2 Flexibility Options in a ‘Decentralized World’

In the ‘de-centralized world,’ the generation capacities are spatially more evenly distributed as well as the storage capacities. Therefore, the grid infrastructure for large distance transmission is also limited. The probability for precise generation forecasting decreases due to the high number of participants and the high uncertainty on effective available renewable generation (downtime of plants). All together these are arguments for an increasing need for demand side flexibility. In addition to the already mentioned energy services for DSM in the ‘centralized world,’ additional technologies would be integrated like air-conditioning and ventilation systems, freezers and refrigerators, other white appliances, small night storage heater and heat pumps, and other tertiary sector processes. By including these technologies, the theoretical potential for DSM increases. To which extent is investigated in the

REFLEX project and thus, is rather a model results than a scenario assumption (cf. Part III). The abovementioned DSM potential focuses mainly on households and tertiary sector. The DSM potential of industry under such scenario is unclear. The potential is determined among others by production process (batch vs. continuous), produced product (storable over hours vs. storable less than an hour vs. non-storable), company-internal workflows (flexible working hours vs. non-flexible ones), provision of energy (internal vs. external and batch vs. continuous) and organization of supply and demand chains (just-in-time vs. batch). In the ‘decentralized world,’ a strong ability of industrial process flexibility is assumed, however, limited by thermodynamic and economic constraints. The latter means, that technical flexibility potentials are only exploited as long as these are not contradicting the profit-orientation of industry companies. To which extent the flexibility potentials are present needs to be investigated and is therefore a project result.

The relevance of flexibility options within the mobility sectors mainly depends on the market penetration of electric mobility as well as mobility services and autonomous driving cars in car sharing fleets. On the one hand, fleet operators can shift charging processes during the day taking the passenger transport demand situation into account. On the other hand, the availability of better infrastructure allows also private users to adapt their preferences to a different daily charging profile. Compared to today’s charging strategies (mostly at home and in the evening), electric cars can be charged during off-peak hours.

As mentioned above, the abundance of available off-peak electricity and some technical impediments could reduce the role of power–to–x technologies as a flexibility option. Furthermore, as long as no small scale applications of power–to–x technologies are developed, the demand for electricity by the technology could outmatch the available off-peak electricity within a region.

2.6 Conclusions

According to the political aim of most member states of the EU and the one of the European Commission, the future energy system will be dominated by a high share of RES, of which wind and solar energy are characterized by high intermittency. To manage this system, economic flexibility potentials have to be identified and quantified. Within REFLEX the analysis of the flexibility potential is based on two main scenarios: Mod-RES and High-RES (decentralized/centralized). The first consideration shows a high interrelationship between the design of the energy system and the flexibility potentials. However, a further elaboration of the interdependencies is necessary. Considering the energy system as a socio-technical system, both discussed scenarios are based on different societal demands regarding the underlying aims of the transformation process, i.e., whether ‘only’ climate change shall be taken into account or whether the transformation is also used to realize a ‘more democratic’ provision of energy. Both scenarios characterize a possible pathway for transformation with highlighting two probable characteristics under the assumption that the overall framework will not be altered by reality until 2050.

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Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO_2 emissions from new passenger cars

Chapter 3
Model Coupling Approach for the Analysis of the Future European Energy System

Robert Kunze and Steffi Schreiber

Abstract In REFLEX ten different bottom-up simulation tools, fundamental energy system models, and approaches for life cycle assessment are coupled to a comprehensive Energy Models System. This Energy Models System allows an in–depth analysis and simultaneously a holistic evaluation of the development toward a low–carbon European energy system with focus on flexibility options up to the year 2050. Different variables are exchanged among the individual models within the Energy Models System. For a consistent analysis, relevant framework and scenario data need to be harmonized between the models.

3.1 Introduction

Model-based energy system analyses have been used successfully for many decades to evaluate and forecast the influences of political and techno-economic framework conditions on system development (e.g., EC 2016, 2018; Keramidas et al. 2020). While the initial focus of model development was primarily on the creation of analysis tools with a total system view, the latest change in the energy landscape and the associated enormous variety of new aspects and options for system design in recent years has led to the development of a broad spectrum of models, each with a specific analysis focus. The main reason for this is that the complexity of new trends in the areas of energy supply and use (e.g., decentralization and sector coupling as well as new actors, technologies, and possibilities for energy source change) cannot be taken into account with the required level of detail within a single model approach. However, the comprehensive and cross-sectoral system view still plays an important role, as there are numerous interdependencies along the entire energy value chain. Thus, the coupling of total and detailed partial models to a consistent Energy

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Models System (EMS) is the decisive key to consider the interactions of relevant techno-economic options in the development of sustainable energy supply strategies adequately.

The core objective of REFLEX is to analyze and evaluate the development toward a low-carbon energy system with focus on needed flexibility options in Europe. In order to answer the research questions of the project, an interdisciplinary approach is chosen by combining analytical methods and tools from the research fields of techno-economic learning, energy system modeling as well as environmental and social life cycle assessment (LCA).

To link and apply the specific approaches of these three research fields in a compatible way, an innovative Energy Models System was developed. This Energy Models System comprises ten individual models that were originally developed as standalone applications by different institutions. The model pool in REFLEX contains bottom-up simulation tools and fundamental energy system models on national and European level as well as approaches for environmental and social life cycle assessment (eLCA, sLCA). These models are coupled based on a common database that contains the harmonized scenario and framework data for all models and serves at the same time for the exchange of intermediate results between the models.[1]

The data-side coupling of independently developed model approaches poses a number of challenges with regard to different levels of aggregation (spatial, sectoral, technological, etc.) and time related structures (yearly, hourly, etc.) of the needed input data and provided result data. Furthermore, the models use different identifier structures and labels as well as varying file formats. In order to manage those challenges and to enable a smooth data exchange between the models, a special interface tool for the common database was developed. The interface is adapted to the specific data needs of each model and allows a comprehensive mapping of data sets. This ensures that each model can read its result data into the database without reformatting, and each model that reuses this data receives it directly in the required structure and format.

3.2 Description of Applied Models

This section gives a brief overview of the models applied in REFLEX and their specific focus. The models can be grouped into three fields (cf. Fig. 3.1): (i) energy supply and markets, (ii) energy demand and (iii) impacts on the environment and society. The EMS covers the electricity, heat, and hydrogen supply sectors as well as all sectors on the demand side (industry, tertiary, residential, and transport sector). The interlinkage of the models allows an adequate consideration of interdependencies between all sectors such as interrelations between energy prices and demand.

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[1] Most of the input and result data are open access available via following data platform: https://data.esa2.eu/tree/REFLEX.

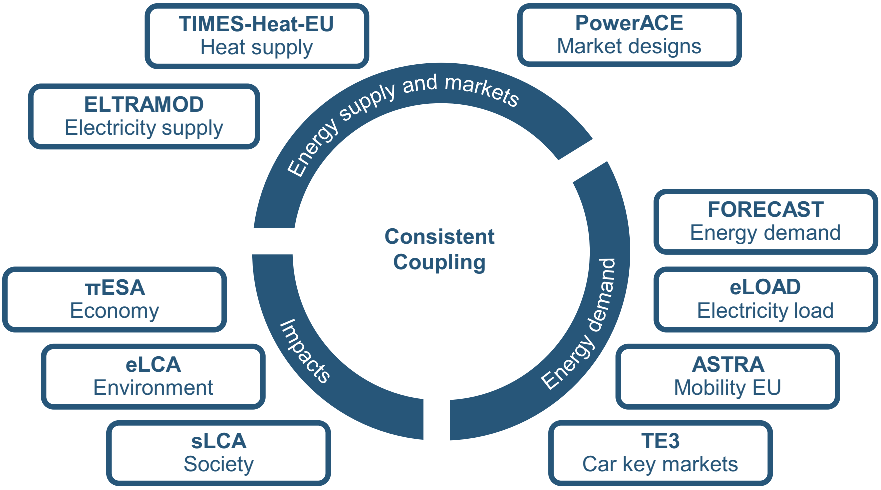

Fig. 3.1 Schematic categorization of applied models in the REFLEX Energy Models System (*Source* Own illustration)

- ***ELTRAMOD*** analyzes the development and operation of electricity generation capacities, storage facilities, and further flexibility options in the European electricity system.
- ***TIMES-Heat-EU*** is applied for modeling the heat supply sector by heat-only as well as combined heat and power (CHP) plants.
- ***PowerACE*** analyzes the impact of different electricity market designs (energy-only market and capacity market) on investments in flexibility options and their contribution to the security of supply at national and European level.
- ***FORECAST*** provides EU-wide projections of the future energy demand in the industry, tertiary and residential sector, considering different types of demand related policies.
- ***eLOAD*** transforms yearly electricity demand into hourly load curves, considering demand side management.
- ***ASTRA*** simulates the transport system development as well as the resulting energy demand in the European transport sector considering all modes of transport.
- ***TE3*** focuses on the road passenger transport with focus on the development of various driving technologies in global key markets.
- ***eLCA*** and ***sLCA*** assess impacts of the energy systems on environment and society.
- ***πESA*** calculates changes of environmental states with respect to air quality and human health.

Essential aspects of the individual models are briefly presented in the following.

3.2.1 ELTRAMOD

(by Technische Universität Dresden)

3.2.1.1 General Information

ELTRAMOD (Electricity Transshipment Model) is a fundamental, deterministic and linear optimization model, which is implemented in GAMS®[2]. It calculates the cost-minimal investments and dispatch in additional power plant capacities, storage facilities and power-to-x-technologies (i.e., power-to-heat, power-to-gas) in the European electricity market by assuming full competition and perfect foresight (Schreiber et al. 2020; Zöphel et al. 2019; Ladwig 2018; Schubert 2016). The model includes the EU-27 member states plus United Kingdom, Norway, Switzerland, and the Balkan countries. Electricity trading between market areas is determined endogenously by the model and limited by net transport capacities (NTC) while the electricity grid within one country is neglected. Each country is treated as one node with country specific hourly time series of electricity and heat demand as well as renewable feed-in. Within ELTRAMOD all relevant policies concerning the European electricity market are implemented, such as the feed-in priority of renewable energies in each country with the respective regulatory framework. To ensure priority feed-in, curtailment is possible without penalty payments. The EU emission trading system (ETS) is modeled implicitly by considering prices for CO_2 emission allowances. Within the REFLEX project ELTRAMOD is used to analyze the penetration of different flexibility options and their contribution to RES integration as well as the interdependencies among various flexibility options in the European electricity system, taking existing regulatory frameworks into account. Furthermore, crucial flexibility measures for achieving the transformation toward a low-carbon electricity system and supporting policy recommendations are identified.

3.2.1.2 Model Structure

The target function of the linear optimization problem is the minimization of the total system costs, which is the sum of the operational costs, the load change costs for ramping up and down, annualized capacity specific overnight investment costs for additional conventional power plants, storages, and power-to-x-technologies. Due to the size of the optimization problem the model is divided in an investment and a dispatch model. The investment model uses a reduced time frame based on represented weeks selected by a hierarchical cluster algorithm. The results of the investment model are fixed and serve as input for the dispatch model with hourly time resolution (8760 h/a). The main restriction of ELTRAMOD is the energy balance.

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[2] The model code is written in GAMS® language (General Algebraic Modeling System). A CPLEX solver with a barrier algorithm (interior-point method) is used.

For each time step and country this constraint in general ensures that the electricity generation per technology has to be equal to the residual load. Additionally, the curtailed intermittent RES, exported and imported electricity, storage (dis-)charging as well as load increase due to power-to-x-technologies (i.e., power-to-heat, power-to-gas) are part of the energy balance. The investments in new capacities are restricted for some technologies according to national legislation. Due to geographical limitations, it is assumed that the potential of conventional hydro power plants (pumped storage plants, reservoirs) is exhausted. Also, the expansion of nuclear, lignite, and coal power plants is limited based on national policy targets of each country. Further, additional investments in less efficient power plants as plants with gas or oil steam turbines (GasSteam, OilSteam) as well as plants with open cycle gas or oil turbines (OCGT, OCOT) are restricted to the must-run requirements of CHP plants. As part of the model coupling some fuel specific technologies are implemented with exogenous minimal investment restrictions in ELTRAMOD to include results by TIMES-Heat-EU regarding CHP capacities. Furthermore, other technical constraints limit the generation of conventional power plants to the installed capacity and the technology-specific availability. The hourly electricity exchange flows are restricted with the available NTC. Pump storage plants, adiabatic compressed air energy storages and lithium-ion as well as redox-flow-batteries represent the electricity storages within the model. To display the flexibility of storages accurately, both the charge and discharge process as well as the available storage capacity are modeled. Load increasing power-to-heat technologies are dependent on the country specific yearly heat demand and normalized hourly heat profiles. As benchmark technology from the heat sector gas boilers can also cover the heat demand. Power-to-gas applications need to satisfy the yearly hydrogen demand derived from ASTRA based on fuel cell development pathways for the transport sector. Additionally, the yearly hydrogen demand from the industry sector, which results from FORECAST, needs to be covered by further capacity expansion of electrolyzers.

3.2.2 TIMES-Heat-EU

(by AGH University of Science and Technology Kraków)

3.2.2.1 General Information

TIMES-Heat-EU is a bottom-up, linear optimization model built with the use of TIMES generator (Loulou 2008). It belongs to the class of integrated capacity expansion and dispatch planning models.

The objective function maximizes the total surplus of district heat producers. Supply technologies incorporated into the model consist of: (i) combined heat and power plants (CHP), (ii) heat only plants (HOP), (iii) power-to-heat plants (PtH), and (iv) thermal energy storages (TES). The geographical coverage of the model extends over the EU-27 member states plus United Kingdom. Each country considers its own district heat systems with no trade between countries. The modeling time horizon covers the period from 2015 to 2050 with 5 years' time steps. Each modeling year is further divided into 224 time-slices derived by aggregating the data every three hours in seven days for four seasons (8 x 7 x 4). The annual district heat demand, which is the exogenous parameter into TIMES-Heat-EU model derived from the FORECAST model, is split into three categories depending on the end-use sector i.e., residential, tertiary or industry. For the first two sectors the annual demand is split into individual time-slices mainly taking into account the variations of the outdoor temperature, whereas for industry it is split rather evenly.

TIMES-Heat-EU considers major EU policies related to district heating (e.g., requirements for high efficiency cogeneration). Some more detailed operational constraints (power-to-heat ratios or ramp rates) were also defined. The EU emission trading system (ETS) is modeled implicitly with the help of CO_2 allowance prices and emission factors for individual fuels.

Within the REFLEX project the TIMES-Heat-EU model assesses the transition pathways towards more sustainable district heat supply and analyzes the role of district heating (DH) systems in enhancing energy system flexibility.

3.2.2.2 Model Structure

TIMES-Heat-EU solves the linear programing problem of district heat supply. The optimization is constrained by a set of equation and inequalities, which include (i) commodity balance equations for district heat, electricity, fuels and emissions, (ii) annual overall efficiency requirements for CHPs in compliance with the EU legislation, (iii) required share of electricity generated in highly efficient cogeneration, and (iv) ramping constraints for the operation of units. The model is optimizing the entire modeling time period with perfect knowledge of the conditions in each time-slice (i.e., perfect foresight approach). The model runs iteratively. Each new iteration step is running with an updated district heat price that is calculated based on the results of the previous run as weighted average production costs plus margin. CHP plants sell the electricity at the wholesale prices determined by ELTRAMOD.

Inelastic demands are assumed in each modeling time-slice. These DH demands must be satisfied by DH generators, PtH and outflows from the thermal energy storages (TES). Heat storage technologies are divided into two groups: (i) short time storages, operating on daily basis, with storage capacity up to one week, and (ii) inter-seasonal storages, operating on seasonal level. All TES technologies are modeled as three step processes, i.e., with input and output processes, in which capacity is represented by the unit of power as well as the storage process, in which the capacity is represented by the unit of energy. PtH technologies, which are represented by electric boilers and heat pumps, can use the electricity that would be otherwise curtailed (free of charge) or simply buy electricity by paying the electricity wholesale price.

The CHP plant operation is therefore driven by three main factors: (i) district heat prices, (ii) wholesale electricity prices and (iii) turbine specified technological restrictions. Moreover, the required quota of electricity from CHPs is specified, e.g., in the Mod-RES and High-RES centralized scenario it is required that 12% of total electricity produced is provided by CHPs.

3.2.3 PowerACE

(by Karlsruhe Institute of Technology)[3]

3.2.3.1 General Information

PowerACE is an agent-based simulation model developed for the analysis of European electricity markets in long-term scenario analyses. The model runs at hourly resolution (8760 h/a) over a typical time horizon from 2015 up to 2050. PowerACE covers different market segments with a focus on the day-ahead market and different types of capacity remuneration mechanisms. Various agents represent the associated market participants, such as utility companies, regulators, and consumers. The electricity suppliers can decide on the daily scheduling of their conventional power plants and storage units as well as on the construction of new conventional generation or storage capacities. Thus, the short-term and long-term decision levels are jointly considered and their interactions can be investigated. Ultimately, the development of the markets emerges from the simulated behavior of all agents.

3.2.3.2 Model Structure

PowerACE is structured into different market areas, in each of which multiple traders are active on the day-ahead market. All agents participating in the market first create a price forecast and then prepare hourly demand and supply bids. The bid prices for the supply bids are primarily based on the variable costs of the respective power plant. In addition, the price forecast is used to estimate the running hours of each power plant and to distribute the expected start-up costs accordingly. Further, price-inelastic bids for demand, renewable feed-in and storage units are prepared by a single trader per market area, respectively. Once all bids have been prepared, they are submitted to the central market coupling operator. In the market clearing process, supply and demand bids are matched across all market areas, such that welfare is maximized subject to the limited interconnector capacities between the different market areas. For a formal description and details of the market coupling and clearing see Ringler et al. (2017). As a result, the information about which bids have been partly or fully accepted is returned to the different traders. Final outcome of the day-ahead market

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[3] This model description is based on Fraunholz and Keles (2019).

simulation is a market clearing price and corresponding electricity volume for each simulation hour and market area.

In addition to the short-term decisions on the day-ahead market, the different utility companies modeled as agents in PowerACE can also perform long-term decisions on investments in new flexible power plant and storage capacities at the end of each simulation year. Contrary to the common approach of generation expansion planning with the objective of minimizing total future system costs, again an actor's perspective is taken. Consequently, investments are only carried out if expected to be profitable by the investors according to their respective annuities. The decisions of the different investors are primarily based on their expectations regarding future electricity prices. As these, vice versa, are influenced by the investment decisions of all investors in all interconnected market areas, a complex game with multiple possible strategies opens up. To find a stable outcome for this game, a Nash-equilibrium with the different market areas as players needs to be determined. Therefore, the expansion planning algorithm terminates when all planned investments are profitable and at the same time none of the investors is able to improve his expected payoff by carrying out further investments, i.e., there is no incentive for any investor to unilaterally deviate from the equilibrium outcome. More details on the expansion planning algorithm are described in Fraunholz et al. (2019).

For the application of PowerACE within REFLEX, the representation of different capacity remuneration mechanisms (central buyer mechanism and strategic reserve) is an essential element. A detailed description of the modeled mechanisms is provided in Keles et al. (2016).

In the market areas with an active central buyer mechanism, annual descending clock auctions are carried out in order to contract a specific amount of secured generation and storage capacity. The regulator first sets a reserve margin, which is calculated as the ratio between secured capacity and maximum peak residual demand in the respective year, excluding imports. Next, the different utility companies provide capacity bids consisting of volume and price. Existing capacity and investments expected to be profitable even without additional capacity payments bid into the auction at zero cost. The bid price for additional investments is determined based on the additional income that would be needed to recover all cost related to the respective investment, the so-called difference costs. Finally, the auction is cleared and all successful participants are compensated with a uniform capacity price.

If active in the respective market area, the strategic reserve is contracted once every simulation year via a uniform price auction. The regulator sets a specific capacity target to be procured and the different utility companies can then offer their conventional generation capacities. Once part of the strategic reserve, a power plant is no longer allowed to participate in any other market. For this reason, earnings from the strategic reserve have to cover all yearly costs of a given power plant, namely fixed costs for operation and maintenance as well as opportunity costs for lost income from e.g., the day-ahead market. The contracted power plants are then only being used by the regulator as a last resort in extreme scarcity situations.

3.2.4 FORECAST

(by Fraunhofer ISI and TEP Energy GmbH)[4]

3.2.4.1 General Information

The FORECAST modeling platform aims to develop annual long-term scenarios for the sector-specific simulation of annual final energy demand of individual countries and world regions until 2050. The modeling is based on a bottom-up approach considering characteristics of individual demand sectors, dynamics of technologies and socio-economic drivers. The model allows to address research questions related to energy demand including scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas emissions as well as abatement cost curves and ex-ante policy impact assessments.

3.2.4.2 Model Structure

FORECAST comprises four individual modules, each representing one sector with high resolution according to the Eurostat (or national) energy balances: the industrial, tertiary and residential sector as well as the module "other sectors" including the agriculture and transport sector in a more aggregated form (Fleiter et al. 2018; Elsland 2016; Jakob et al. 2012; cf. Fig. 3.2). While all sector modules follow a similar bottom-up methodology, they also consider the particularities of each sector like technology structure, heterogeneity of actors and data availability.

In Fig. 3.2 a schematic overview of the FORECAST model structure is illustrated. Next to the scenario definition data (e.g., gross domestic product or policy intensity), the FORECAST platform contains a macro module that determines the activity variables for the individual modules and sectors (e.g., gross value added by industrial sub-sectors and past trends). A second module forecasts sectoral retail prices by considering production or trade prices and various tax and fee components. Each of the four sector modules is divided into three hierarchical levels, i.e., the industrial sector is clustered in (i) industrial sub-sectors (branches) (ii) differentiated according to sector-specific processes and (iii) process- or technology-specific savings options, for instance.

The main advantage of the bottom-up simulation model FORECAST is its high degree of technological detail. Each sector requires sector-specific activity data, like industrial production in the industry sector and the number of households in the residential sector. Furthermore, end-consumer energy prices play an important role in each sector as they are distinguished by energy carrier. The third group of input data, the technology characterization also reflects data availability of the individual sectors.

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[4] The model description is based on Fraunhofer ISI et al. (2017).

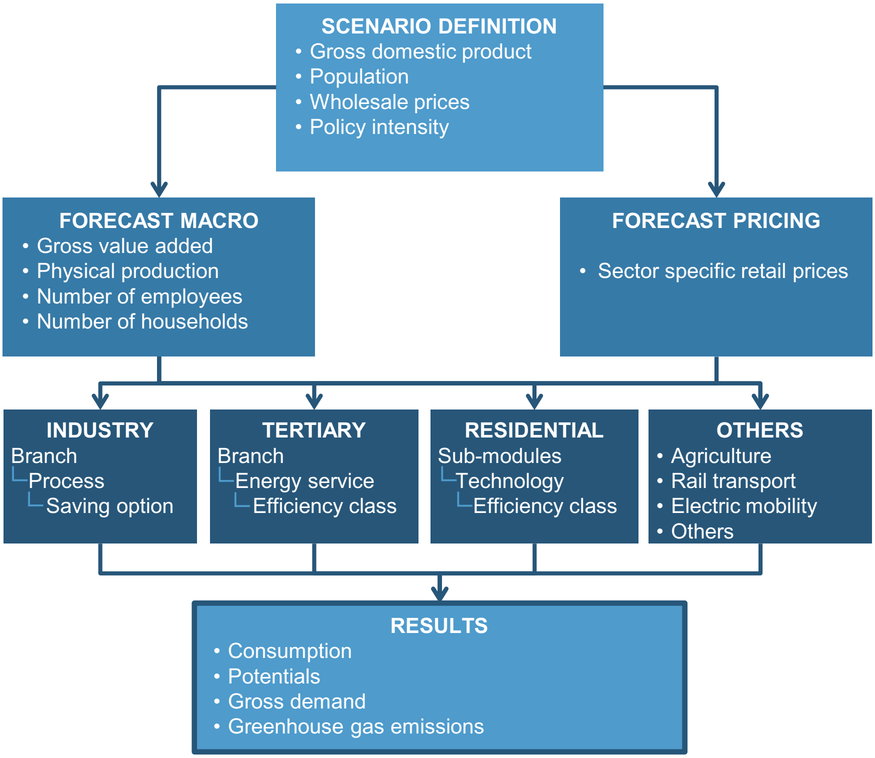

Fig. 3.2 Schematic overview of FORECAST model structure. Figure adapted and based on Fraunhofer ISI et al. (2017)

While in the industry and tertiary sector the model works with so-called energy-efficiency measures (EEMs), which represent all kinds of actions that reduce specific energy consumption, in the residential sector the stock of alternative appliances and the market share of different efficiency classes are explicitly modeled. In all cases, energy savings can be calculated and traced back to technological dynamics including cost considerations. As a result of the bottom-up approach model results can be disaggregated with a very high resolution comprising sectors and sub-sectors, but also end-uses technologies and energy carriers.

In addition to the national analysis, the FORECAST platform also includes a module for regional analysis of electricity demand. The regional module uses technology- and sector-specific distribution keys to calculate a spatially resolved demand differentiated by NUTS3 regions (administrative districts and independent cities). This is based on extensive data analyses of structural data, including the spatial distribution of population, households, employees, industrial locations, and weather data.

In REFLEX, the FORECAST model is primarily responsible to provide projections for the future energy demand, considering different types of demand related policies. The demand projections cover different energy carriers and are available on an annual basis. The yearly electricity demand is further transformed into hourly load curves by the eLOAD model.

3.2.5 eLOAD

(by Fraunhofer ISI)[5]

3.2.5.1 General Information

The eLOAD (electricity LOad curve ADjustment) model has been developed to project future electricity load curves on a national level based on application specific hourly load profiles. The model assesses the transformation of the load curve due to structural and technological changes on the demand side. This also includes demand response (DR) measures through the flexible use of new technologies, which can lead to a smoothing of the residual load. For this purpose, cost-optimal load shifting activities of suitable appliances such as cooling devices or electric vehicles are determined based on a mixed-integer optimization for the demand side. The results of eLOAD can provide information on future peak loads and load ramp rates, which are important parameters for investment decisions regarding the development of needed generation capacities and grid infrastructure.

3.2.5.2 Model Structure

The deformation of the load curve due to structural changes and the integration of new technologies on the demand side is modeled with the first module of eLOAD. In this module, the method of partial decomposition is used. The method applies a database with more than 600 technology-specific load profiles from field studies, building simulations and industrial projects, to cope with the great variety of individual load structures on the demand side. With the additional consideration of weather data, the partial approach thus allows a transformation of the historical load curve profile in dependence of future changing electricity applications while characteristic irregularities and stochastic outliers from the historical load curves are preserved.

The role of eLOAD in REFLEX is twofold. First, eLOAD translates the annual electricity and heat demand projections delivered by the FORECAST model into hourly load curves. While electricity load curves serve as an input for the electricity market models ELTRAMOD and PowerACE, the heat load curves are transferred to the TIMES-Heat-EU model.

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[5] The model description is based on Gnann et al. (2018).

Second, eLOAD is required to estimate technology distinct demand response potentials. These potentials are characterized by seasonal, weekly, and daily variations and depend on the dynamic tariff mechanism considered. The eLOAD results allow to draw conclusions on the potential contribution of demand response for peak load shaving and the integration of renewable energy sources and on the extent to which the potential is affected by energy-efficiency policies. In addition, the demand response potentials are used in the ELTRAMOD model in the framework of a system optimization approach that determines the cost-optimal mix of flexibility options to ensure a stable European electricity supply system.

3.2.6 ASTRA

(by Transporti e Territorio and Fraunhofer ISI)

3.2.6.1 General Information

ASTRA (ASsessment of TRAnsport Strategies) is an integrated assessment model that simulates the transport system development in combination with the economy and environmental impacts until the year 2050. The model is based on the System Dynamics approach and built in Vensim®. Geographically, ASTRA covers all EU-27 member states plus Norway, Switzerland, and the United Kingdom.

A strong feature of ASTRA is the ability to simulate and test integrated policy packages and to provide indicators for the indirect effects of transport on the economic system (e.g., GDP growth, employment). Strategic assessment capabilities in ASTRA cover a wide range of transport measures and investments with flexible timing and levels of implementation. Potential policies include vehicle technologies, infrastructure development, pricing, taxation, speed limits, and trade policies etc. The model produces outcomes for diverse impact types; in particular transport system operation, economic, environmental, and social indicators. ASTRA has been successfully applied for transport, renewable energy, and climate policy assessments as well as for technology and scenario analysis. For such analyses the ASTRA model has often been coupled to bottom-up techno-economic models. The model has been applied for national as well as EU-wide studies addressing the following topics:

- **Transport policy assessment**: pricing, taxation (on fuel or vehicle), emissions and efficiency standards, infrastructure investments
- **Technology and scenario analysis**: alternative vehicle technology (e.g., electric and fuel cell vehicles), integrated energy and transport policy (e.g., vehicle efficiency improvement)
- **Renewable policy assessment**: subsidies, feed-in tariffs, investment strategies
- **Climate policy assessment**: and energy price trends

3.2.6.2 Model Structure

As illustrated in Fig. 3.3, ASTRA consists of six different modules, each related to one specific aspect such as the economy, transport demand, or the vehicle fleet. These modules are linked and interact with each other via direct effects and feedback mechanisms. The main modules cover the following aspects:

- Population and social structure (age cohorts and income groups)
- Economy (input–output tables, employment, consumption, and investment)
- Foreign trade (inside EU and to partners from outside EU)
- Transport (demand estimation, modal split, transport cost, and infrastructure networks)
- Vehicle fleet (passenger and freight road vehicles)
- Environment (pollutant emissions, CO_2 emissions, and fuel consumption).

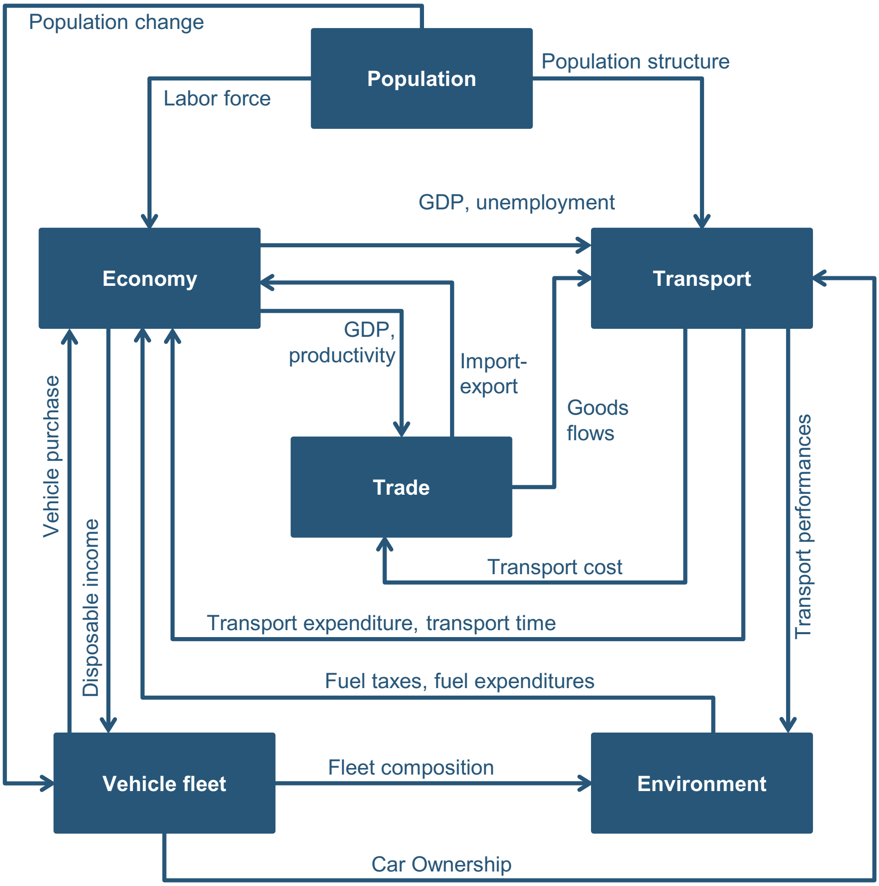

Fig. 3.3 The ASTRA model structure (*Source* Own illustration)

The economy module simulates the fundamental economic variables. Some of these variables (e.g., GDP) are transferred to the transport generation module, which uses the input to generate a distributed transport demand. In the transport module, demand is split by mode of transport and traffic performance is calculated. The environment module uses inputs from the transport module (in terms of vehicle-kilometers-traveled per mode and geographical context) and from the vehicle fleet module (in terms of the technical composition of vehicle fleets), in order to compute energy consumption, greenhouse gas, and air pollutant emissions.

To analyze sustainable transition scenarios, the model was enhanced by alternative drive technologies for vehicle fleets, new mobility concepts and behavioral change options toward active modes (Martino et al. 2018, 2019).

The diffusion of alternative drive technologies for road vehicles is simulated in the vehicle fleet module based on an adapted Total Cost of Ownership (TCO) approach separately for different vehicle categories. These categories comprise private and commercial cars, light duty vehicles, and heavy duty vehicles in four gross vehicle weight categories, urban buses, and coaches. Based on the technical characteristics of available fuel options today and in the future and the heterogeneous requirements of the different users, a set of fuel options is available for each vehicle category. Technologies cover gasoline, diesel, liquefied petroleum gas, compressed, and liquefied natural gas (LNG), battery electric vehicles, plug-in hybrid electric vehicles, fuel cell electric vehicles, and trolleys for urban buses and long-distance trucks. Non-road vehicle fleets like inland waterways, maritime ships, air planes, and railways are modeled in less detail due to a lack of detailed statistics, long average lifetimes, and only few renewable fuel options imaginable for the time horizon until 2050. As alternative fuel options, ASTRA considers blended kerosene with biofuels for planes, an increasing share of electrified traction for railways, and biodiesel and LNG for maritime ships and inland waterways.

As the number of car-sharing users grew rapidly in many EU member states and active modes are becoming more popular in several cities, specific algorithms were implemented to simulate the diffusion of car-sharing mobility services and their impacts on mobility indicators; furthermore, the active passenger transport modes walking and cycling were explicitly considered for urban areas.

In REFLEX, ASTRA is coupled with the models FORECAST, eLOAD, and ELTRAMOD to simulate feedback mechanisms between electricity consumption patterns and prices and with the TE3 model to consider global learning effects for electric vehicle diffusion.

3.2.7 TE3

(by Karlsruhe Institute of Technology)

3.2.7.1 General Information

TE3 (Transport, Energy, Economics, Environment) is a multi-country computer simulation model capable of generating scenarios and suitable for policy analysis. The TE3 model is a simplified representation of the road passenger transport system, with focus on car travel activity and car powertrain technologies. Given the complexity and uncertainty of the system under study, systems thinking and scenarios analysis are adopted as a guiding research principle and methodology, respectively. The TE3 model has been developed by applying the System Dynamics (SD) approach and is implemented in the Vensim® platform. The methodology is mixed, as the model contains elements of other methods. In particular, the modeling exercise underlying TE3 can be divided into three main steps:

1. Projection of the total car stock by means of an aggregate econometric model;
2. Simulation of market shares by car technology by means of a discrete choice modeling framework; and
3. Estimation of energy use and greenhouse gas emissions by means of an accounting framework.

3.2.7.2 Model Structure

The TE3 model illustrates future development pathways for car technologies (nine powertrains) and offers an international perspective by covering six main car markets (China, France, Germany, India, Japan, US). In REFLEX the TE3 focus is on four non-European markets. The time horizon is limited to the period from 2000 to 2050. The model accomplishes its objective by creating scenarios of the dynamic market penetration of alternative car technologies, considering direct and indirect emissions, and incorporating a set of policy measures. TE3 can be regarded as a hybrid model, as it follows an approach that contains top-down and bottom-up features. Core to the TE3 model is the representation of feedback loops. A modular approach, which is illustrated in Fig. 3.4 is implemented with the following interlinked nine modules:

- **Population GDP**: Incorporates external projections on population and gross domestic product;
- **Car stock**: Projects car ownership, resulting aggregate car sales as well as the simulation of the market shares by car technology;
- **Travel demand by car**: Estimates travel demand by car and energy;
- **Infrastructure**: Determines the deployment of public refueling and recharging infrastructure;
- **Technology choice**: Comprises of the model's main behavioral assumptions;
- **Production costs:** Considers three broad classes of car attributes—technical features, production costs, and consumer costs;
- **Energy**: Contains energy prices, electricity mix, and energy use;

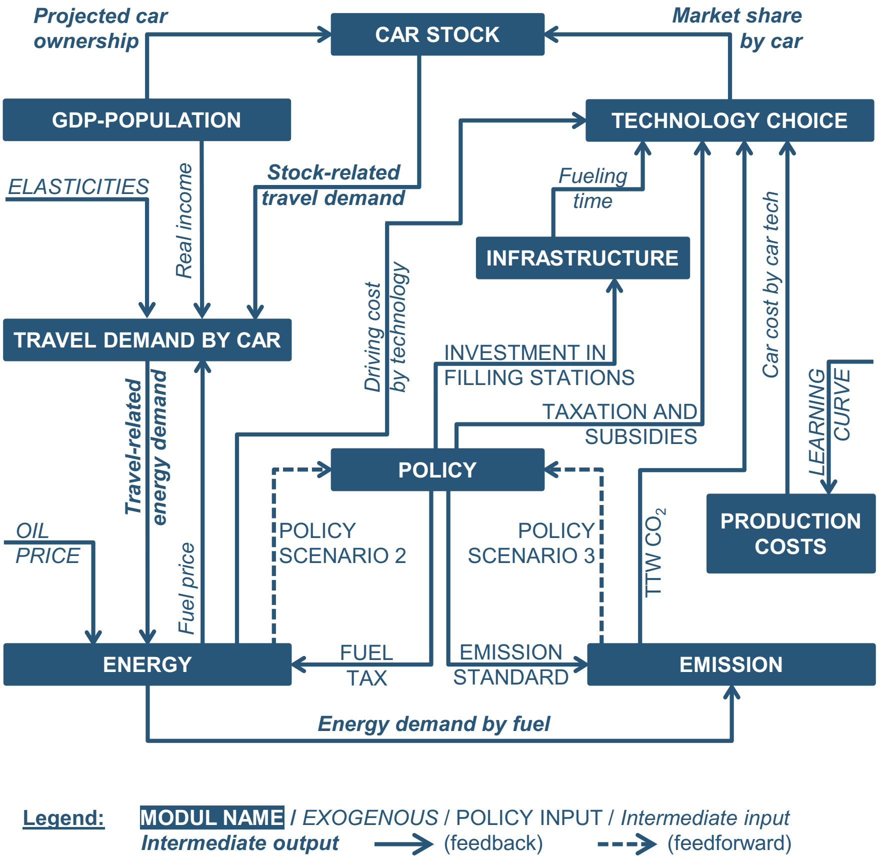

Fig. 3.4 Overview of the TE3 model structure with main linkages between modules. Figure adapted according to Gomez Vilchez et al. (2016)

- **Emission**: Calculates corresponding GHG emissions divided into six sub-modules—emission factors, new car emissions, manufacturing and scrappage, tank-to-wheel (TTW), well-to-tank (WTT), and life cycle; and
- **Policy**: Facilitates policy analysis.

3.2.8 eLCA and sLCA

(by Karlsruhe Institute of Technology and KTH Royal Institute of Technology)

Environmental life cycle assessment (eLCA) and social life cycle assessment (sLCA) are two variants based on the general setting of the life cycle assessment (LCA) methodology (ISO 2006). The application of the standardized LCA method urges a precise model-based setting of life cycle thinking. Life cycle thinking considers the impacts on the environment or society due to the entire process chain ("cradle to grave") to disclose hotspots affected along the process chain of technology or system under investigation (Heiskanen 2002; Xu et al. 2020).

In the REFLEX project, the main objective was to develop a transparent model-based setting for environmental and social impact assessment using inputs among others from large energy system models (ESMs) where the changes in energy technologies, supply chains, and systems are accounted for. A more detailed description of the general structure and the coupling of the LCA tools with the ESM is given in Sect. 3.3.

3.2.9 πESA

(by AGH University of Science and Technology Kraków)

3.2.9.1 General Information

As a platform for an Integrated Energy System Analysis πESA (spoken Pi-ESA) is used to analyze the changes in air quality and human health impacts associated with different energy scenarios. The concept of πESA is based on the Driver-Pressure-State-Impact-Response (DPSIR) framework. The main element of πESA is the Polyphemus Air Quality System (Mallet et al. 2007). It employs the Eulerian chemistry-transport-model called Polair3D that enables to track atmospheric dispersion of air pollutants. The spatial domain of πESA can be freely set and mainly depends on the availability of data that are needed to perform simulation runs. In the REFLEX project the modeling domain covers Europe with the geographical extend of 12.0°W, 27°E of longitude and 35.0°N - 69°N of latitude. The horizontal resolution was set to 1.0° x 1.0° (along longitude and latitude, respectively). Five vertical levels were used with the following limits (in meters above surface): 0, 50, 600, 1,200, 2,000, and 3,000. The results of pollutants concentration recorded in the first vertical level i.e., from 0 m to 50 m were used to analyze the health impacts. πESA considers only the health impact due to people's long-term exposure to fine particulate ($PM_{2.5}$) air pollution. The main indicator calculated by πESA is the Loss of Life Expectancy (LLE), which is often used as a proxy for quantifying the overall impact on a population's health. In addition, πESA estimates newly observed cases of Chronic Bronchitis (CB) and the number of days when an individual's routine activities is disrupted due to elevated concentration of $PM_{2.5}$ i.e., Restricted Activity Days. These impacts are calculated using the, so-called, concentration-response functions (CRFs), which relates the quantity of a pollutant that affects a population (accounting for the absorption of the pollutant from the air into the body) to the physical impact.

3.2.9.2 Model Structure

The main component of πESA is the Polyphemus Air Quality System, which structure is depicted in Fig. 3.5. It contains the numerical solver Polair3D used for both gaseous and aerosol species. Polair3D tracks multiphase chemistry: (i) gas, (ii) water and (iii) aerosols and has several chemical mechanisms for gaseous pollutants, heavy metals aerosols, radioactive elements, and inert compounds. Polair3D includes the gas-phase chemical mechanism RACM, the Variable Size-Resolution Model VSRM, the Size-resolved Aerosol Model SIREAM and the Aerosol Thermodynamic Model ISORROPIA. Applied chemical schemes allow to model effects of condensation/evaporation coagulation and nucleation upon the particle size distribution. Additionally, Polyphemus includes a library of physical parameterizations called AtmoData and a set of programs using AtmoData designed to generate data required by Polair3D, e.g., deposition velocities, vertical diffusion coefficients, emissions, etc.

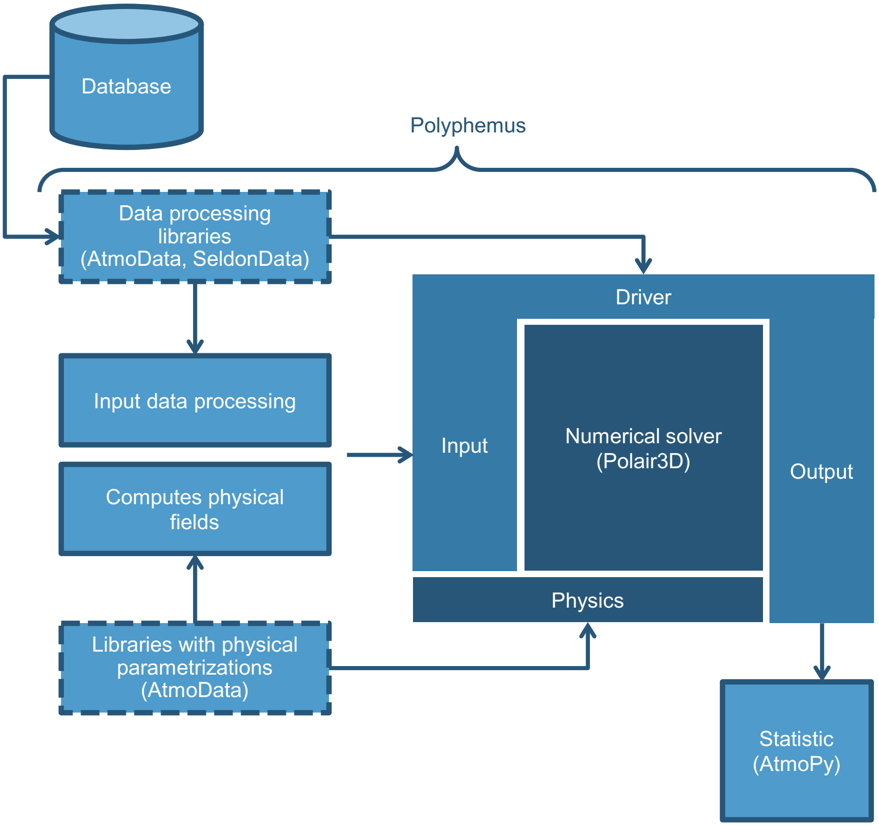

Fig. 3.5 Structure of the Polyphemus Air Quality System—main component of the πESA model (*Source* Own illustration)

The calculations are prepared based on the following data among others: anthropogenic and natural emissions (volume and surface), metrological fields (from the European Centre for Medium-Range Weather Forecasts or the Weather Research and Forecasting Model), initial and boundary concentration and land use data.

The approach to estimate the health impacts of air pollution in πESA is based on the methodology developed within a series of the ExternE projects[6]. Health impacts (*I*) are calculated using the concentration-response functions (*CRFs*), which in general, have the following formulae:

$$I = Con \cdot Pop \cdot Fr \cdot CRF \tag{3.1}$$

I is the health impact of a given type (e.g., years of life lost—*YOLL*, reactive airway disease—*RAD*, chronic bronchitis—*CB*), *Con* is the concentration of $PM_{2.5}$ [$\mu g/m^3$], *Pop* denotes the population exposed, *Fr* is the fraction of population affected and *CRF* is the concentration-response function for a given impact type. $PM_{2.5}$ impacts have been estimated for the full range of observed concentrations. In the last step πESA estimates the external costs by totalizing the monetary values assigned to respective health impacts.

3.3 REFLEX Energy Models System

The specific strengths of the stand-alone models described above are combined in REFLEX for a comprehensive and simultaneously in-depth analysis of the European energy system. Through the model coupling essential exogenous parameters of the individual applications become endogenous variables of the Energy Models System by using relevant output data of one model as input data for another model. In the following the models' interaction within the model-based analysis and the data exchange between the models are described.

To achieve robust results by applying the Energy Models System for each REFLEX scenario, several iterations with the interlinked models have been performed. The calculated intermediate model results were exchanged between the models via a common project database. Figure 3.6 gives an overview about the model coupling and data exchange in REFLEX.

Common scenario framework data and assumptions (e.g., development of population, import fuel prices on EU borders etc.) are harmonized and implemented in the models to provide consistent estimations, before running the Energy Models System. Additionally, initial electricity prices for EU countries are determined.

The following explanations focus exclusively on data exchange between the models. Depending on the focus of analysis, the results of the individual models contain a lot more of additional data and information that are not considered here.

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[6] For more information see http://www.externe.info/externe_d7/.

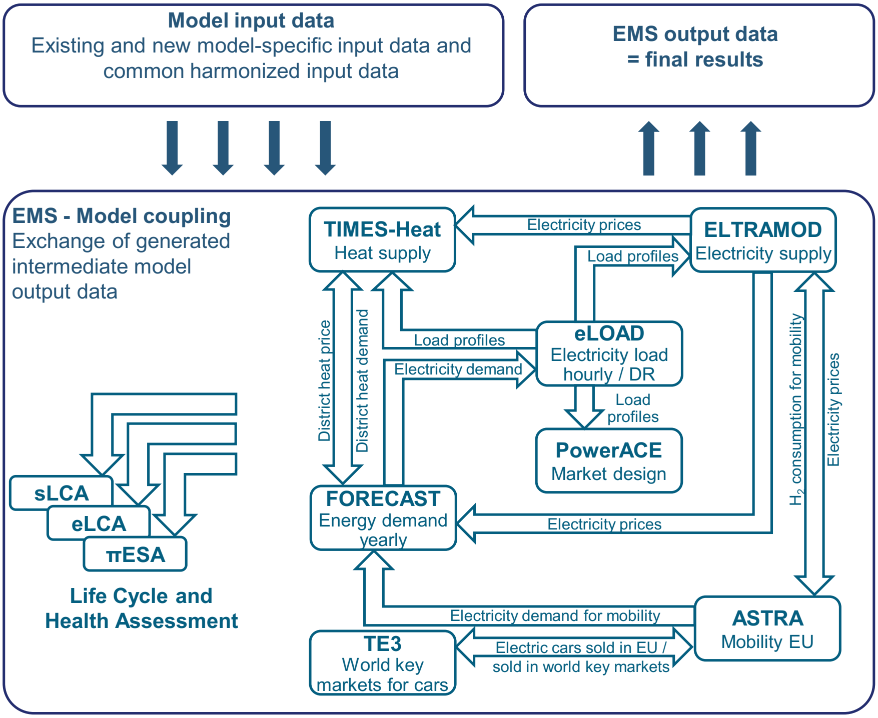

Fig. 3.6 Model coupling and data exchange in the REFLEX project (*Source* Own illustration)

As a first step, the ASTRA model determines the energy demand for mobility in Europe, considering the development of different transport technologies. In order to estimate the market penetration of electric vehicles and the associated global cost effects (future prices of electric vehicle batteries and fuel cells based on the learning curve theory), the development of the road passenger sectors for non–EU key markets is simulated with the TE3 model. In this sense, the global automotive market (especially including Northern America and Asia) is considered for investigating the uptake of alternative car technology in Europe (cf. Heitel et al. 2019). After some iterations between the models to stabilize the results, the electricity demand for mobility calculated by ASTRA is provided to FORECAST with a yearly resolution.

Afterwards, by considering the results of ASTRA for the transport sector, FORECAST performs a projection of the development and annual consumption of all relevant energy carrier for the remaining energy consuming sectors (industry, tertiary and residential sector).

In the next step, the annual electricity demand calculated by FORECAST is provided to the eLOAD model. Within eLOAD, the hourly resolution of electricity demand is modeled while demand response measures are considered. Therefore, specific load curves are used for about 50 different processes and energy applications that vary during a day or week.

The eLOAD model passes the results of hourly electricity demand to ELTRAMOD. In addition, the yearly hydrogen consumption in the mobility sector is provided from ASTRA. ELTRAMOD calculates the optimal investment and concerning additional power plant capacities, storage facilities and power-to-x capacities (e.g., electrolyzers). Furthermore, the optimal dispatch decision of these plants and units is estimated by fulfilling the electricity demand in each hour of a year as well as the yearly hydrogen and heat demand by minimizing the total system costs. The exchange of electricity between EU countries is modeled endogenously and restricted by given net transfer capacities. The calculation of new investments in power plant capacities and electricity price developments are the main results of ELTRAMOD.

While ELTRAMOD focuses on the electricity supply, TIMES-Heat-EU analyzes the heat system in parallel. Both sectors are mainly connected through CHP plants and electric powered heating units, which are considered in TIMES-Heat-EU. Input parameter for TIMES-Heat-EU are ELTRAMOD results such as the annual capacities and hourly operation of all power plants without CHP as well as RES curtailment and the electricity prices. Additionally, TIMES-Heat-EU receives the projection of the annual district heat demand from FORECAST. Thereafter, TIMES-Heat-EU estimates the development of the heat system and determines a projection for the district heat prices, which are returned to FORECAST in preparation for the next iteration loop of the EMS. The results of ASTRA, FORECAST, and eLOAD are highly dependent on the electricity price development provided by ELTRAMOD. Once the models receive the wholesale electricity prices, the next iteration of the EMS can be initialized.

In addition to ELTRAMOD, PowerACE simulates the electricity supply-side too, but focuses more on the analysis of the impact concerning different electricity market designs on investments in flexibility options and security of supply with an agent-based approach. Therefore, as a final step after finalizing the iterations for one scenario, the hourly electricity demand from eLOAD is provided to the PowerACE model. All relevant parameters of the electricity sectors are harmonized between ELTRAMOD and PowerACE (e.g., NTCs, generation efficiency, initial power plant capacities, and decommissioned capacities by power plant age etc.). Beyond that, the models TIMES-Heat-EU, ELTRAMOD and PowerACE deliver input data on installed power plant capacity, energy demand of power plants, operation and electricity generation as well as emissions by country. From the ASTRA model data are provided at country level in terms of energy usage, vehicle stock, employment, and car ownership.

Finally, the LCA tools assess the impacts on environment and society of the projected pathways of the energy system. Therefore, the tools require data describing consumables in the energy systems (i.e., fuels, renewable and non-renewable) as well as capital for each sector of the energy system. FORECAST provides the LCA-based assessment tools with data on final energy demand disaggregated with respect to the energy carrier.

Figure 3.7 illustrates the background framework for coupling the LCA (both eLCA and sLCA) and ESMs of the REFLEX project following the principles of EAFESA,

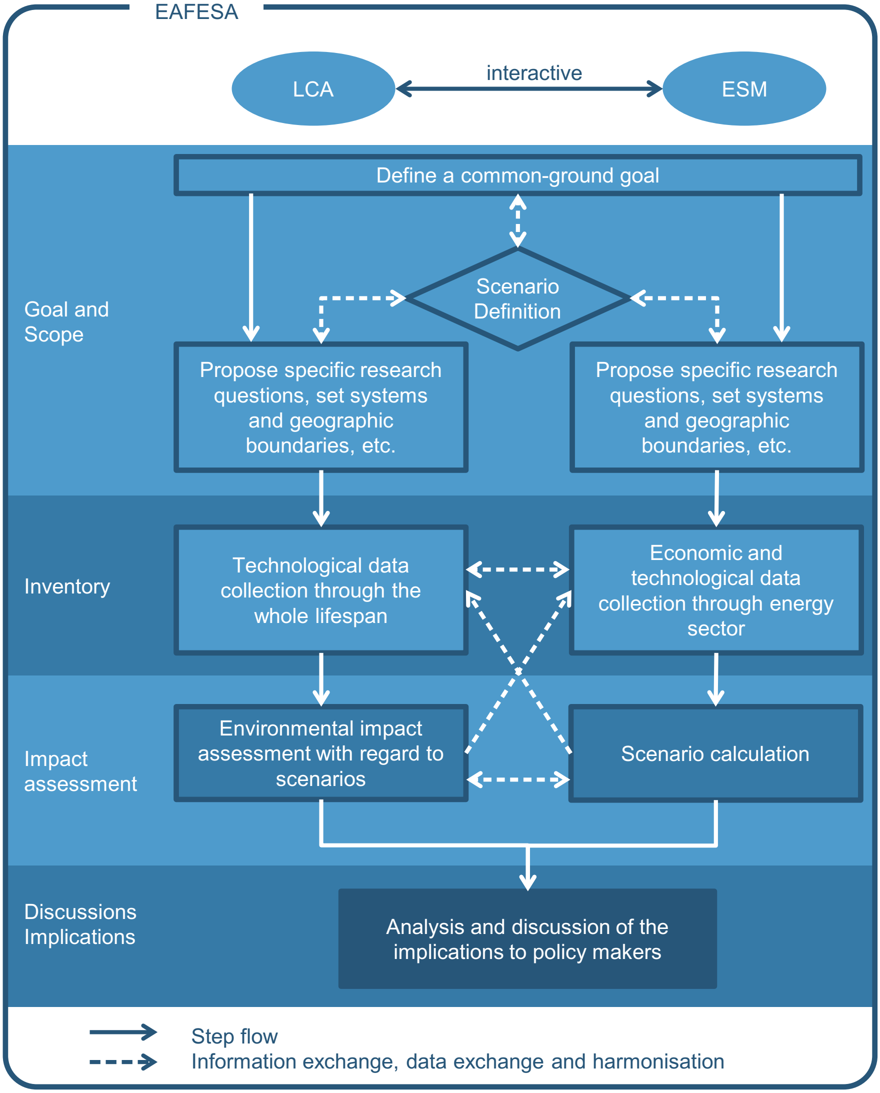

Fig. 3.7 Overview of Environmental Assessment Framework for Energy System Analysis (EAFESA). Figure adapted according to Xu et al. (2020)

Environmental Assessment Framework for Energy System Analysis (Xu et al. 2020). EAFESA guarantees transparency and robustness of the information exchanged and harmonized between the ESMs and LCA. In this regard, EAFESA consists of four steps structured according to the LCA methodology (ISO 2006).

Firstly, EAFESA requests to define a common-ground goal based on the map of technologies considered in the ESMs and LCA. If necessary, technologies need to be disaggregated to merge the system boundaries and scope of ESMs and LCA model-based settings. Secondly, the inventory analysis demands categorizing the needed set of harmonized data for both approaches and, as a follow-up, making the harmonization of the data. The overarching criteria to justify any change in data for emerging technologies is that it should be consistent in light of the overarching scenario that is considered. This step differs between the eLCA and sLCA because of the scope and databases. Thirdly, impact assessment should enable assessment of the societal objectives identified in the objective definition from a social and environmental perspective. In this step, the outcome of each model-based setting is discussed between the ESMs and LCA. The discussion and implication provide two distinct roles. Firstly, life cycle processes that make a significant beneficial contribution to each social and environmental impact category shall be identified. Secondly, unintended environmental and social burdens (cf. PART V Chapters 13 and 14) that should require government attention are identified and discussed.

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Part II
Technological Progress

Chapter 4
Deriving Experience Curves and Implementing Technological Learning in Energy System Models

Atse Louwen and Martin Junginger

Abstract Technological learning encompasses a variety of mechanisms by which technologies improve and decrease in costs. Experience curves are commonly used to analyze and explicitly quantify technological learning. This chapter presents the history and basic methodology of experience curves, and discusses the implementation of experience curves in energy system and sectoral energy models. Several key results of the REFLEX project with respect to state-of-the-art experience curves, and the implementation of experience curves in the REFLEX Energy Modeling System are highlighted. Finally, a set of key lessons learned in the REFLEX project are presented, discussing both methodological issues of experience curves as well as key issues with regard to the implementation of experience curves in different types of energy system and sectoral energy models.

4.1 Introduction

4.1.1 History and Concept

Within the REFLEX project, a large effort was made to include the effects of technological learning in the different energy and transport models that are used within the project. Here, technological learning is considered as a term that encompasses a variety of mechanisms by which technologies can improve, in relation to production costs, efficiency, quality, etc. It includes mechanisms like learning-by-doing, learning-by-searching (R&D), and upscaling. One of the most prominent methods to analyze and quantify technological learning is the so-called 'experience curve.'

The experience curve describes an empirical relationship between cumulative production of a technology and its unit costs. It was developed in the form considered

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here by the Boston Consulting Group, building on work that originated from the aircraft building Curtiss-Wright Corporation (Wright 1936). Wright analyzed the labor costs for each airplane, and found that they decreased for each additional airplane that was manufactured. He showed that the costs followed the following relation:

$$F = N^x \tag{4.1}$$

Here, F is the variation of production cost as a function of the cumulative quantity of airplanes N, and x is the factor that gives the speed with which the labor costs declined. The reciprocal of this formula gives the decline in labor costs with increasing N. With a value of $x = 0.322$ in Eq. (4.1), labor costs declined with 20% every time the cumulative quantity of airplanes produced doubled. This relation, now referred to as the learning curve, was later revisited by different researchers, until the Boston Consulting Group (1970) developed the experience curve, which aimed to include total costs of production (not just labor) and would represent a whole industry of a technology, rather than a single company. They gave the equation the following form:

$$C = C_1 \cdot N^b \tag{4.2}$$

Here the unit costs of a technology C are a function of the cumulative production N, the experience curve parameter b and the costs of the first unit, C_1. With a value of $b = -0.322$, production costs would again decline with 20% for every doubling of N. This also gave rise to two terms associated with the experience curve parameter b, namely the learning rate (LR) and progress ratio (PR), with:

$$LR = 1 - 2^b \tag{4.3}$$

$$PR = 2^b \tag{4.4}$$

The learning rate LR gives the percentage reduction in costs for every doubling of cumulative production N, while the progress ratio PR, is 80% if the learning rate is 20%. The experience curve of Eq. (4.2) is now called the one-factor experience curve (OFEC), as it includes only the cumulative production as a factor explaining costs reductions. Further development of the concept has resulted in the two-factor experience curve (TFEC), which includes a parameter that describes R&D (using R&D expenditures or patent applications as a proxy) and multi-factor experience curves (MFEC) which could include a variety of additional parameters, such as input material prices. As the aim of the REFLEX project is to include technological progress in energy modeling systems, and these models generally do not produce all inputs required for two- or multi-factor experience curves (Louwen et al. 2018), the focus is here on the one-factor experience curves. Figure 4.1 shows an example

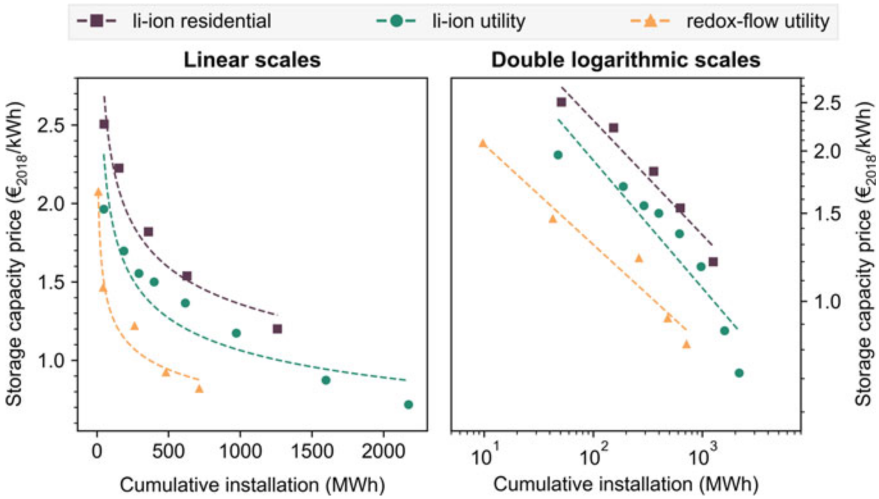


Fig. 4.1 Example of experience curves in linear (left) and double-logarithmic (right) scales. Data for battery storage systems according to Schmidt et al. (2017)

of experience curves for battery storage systems on linear and double-logarithmic scales.

Although not without criticisms, the OFEC is one of the few methods that use an empirical relationship between production costs and cumulative production as a means to forecast future costs of technologies (Junginger and Louwen 2020). In modeling activities, it allows for representing developments in the market diffusion of technologies and gives cost trajectories of the respective technologies over the timeframe of the modeling. In Sect. 4.3, the model implementation of experience curves is discussed in more detail.

4.1.2 *Key Applications of Experience Curves*

The experience curve has two main applications: as a tool in the design and assessment of policy measures, and as a tool with which future cost trajectories can be determined in energy and integrated modeling activities.

For policymakers, the experience curve can be a valuable means to track the cost developments of for instance renewable alternatives for electricity generation, but also to design and assess policy measures that aim to bring down the costs of these technologies. By deriving an experience curve from empirical cost data, a deployment trajectory can be defined, showing how much additional cumulative production is required for the technology to reach a certain competitive cost level. Then, by taking the integral of the experience curve, the so-called ‘learning investments’ can be derived (Louwen and Subtil Lacerda 2020). These learning investments, which are

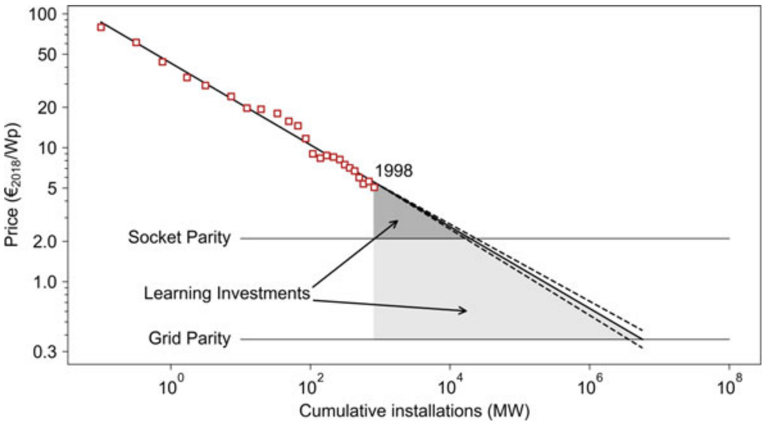


Fig. 4.2 Example of a visualization of the required learning investments to reach a certain level of competitiveness (*Source* Figure taken from Louwen and Subtil Lacerda [2020])

the total cost, minus the competitive cost share, can be considered as the investment that needs to be incentivized through policy measures before the technology becomes competitive without subsidies. In Fig. 4.2 an example is shown that visualizes these learning investments.

A good example of the effect of such policies on driving prices down the experience curve is found for the solar photovoltaic (PV) industry. Due to incentive schemes in several European markets, especially Germany, the demand for PV systems grew rapidly in the past decades. As a result, cumulative production of PV systems increased, and system costs declined. At a later stage, many other local PV markets started growing in response to declining costs, and especially in China installed PV system capacity grew rapidly, resulting in that country now having the largest amount of installed PV system capacity. As a result of the rapid decline in PV system costs, PV generated electricity is now competitive with fossil fuel alternatives in ever more countries (SolarPower Europe 2019).

Another main application of the experience curve lies in energy and integrated modeling activities. Since the main aim of energy and integrated modeling is to give forecasts of future energy and climate systems, a key aspect of this modeling is to be able to model the future costs of energy system technologies. Usually, these future costs could be taken from time-based exogenous cost estimations, but by using experience curves, models can endogenously determine cost trajectories for technologies in response to and in a feedback loop with their modeled market diffusion trajectories. The fact that the experience curve is based on empirical data makes it very attractive in modeling and offers a very simple model formulation of costs *vs.* cumulative production.

By using experience curves, modelers thus have an evidence-based method to calculate future technology investment costs, and as such can model future energy systems while considering the feedback loop between technology cost and market diffusion. This gives both researchers and policymakers a tool with which they can design pathways toward future low-carbon energy systems, and assess the requirements and effects of policy measures that aim to increase market diffusion of technologies or to achieve certain climate change mitigation targets.

4.1.3 Key Issues and Drawbacks of Experience Curves

An overview of several issues and drawbacks of (using) experience curves is given in Junginger et al. (2010) and Junginger and Louwen (2020). Below some key issues will be discussed, related to experience curve parameter uncertainty, system boundaries and functional units, and causality.

4.1.3.1 Experience Curve Parameter Uncertainty

A common issue with deriving curve parameters through regression of empirical datasets, is the uncertainty in the derived parameters. For experience curves this is no different. Cost projections made with experience curves are thus extremely sensitive to uncertainties. However, uncertainty about the value of the experience curve parameters is the result of two issues observed in experience curve studies.

First, a study by Nemet (2009) shows that the learning rate derived from subsets of the complete dataset is not constant, and as a result, a calculation of required learning investments as described in Sect. 4.1.2 can vary wildly. This would suggest that the recommendation is to use datasets that have as long a timeframe as possible. Given the fact that datasets for novel technologies like electricity storage systems are however quite small (Kittner et al. 2017; Schmidt et al. 2017), this means rigorous uncertainty and sensitivity analysis of experience curve parameters is required.

Second, a common problem with (non-)linear regression is that with large errors between measured and modeled data, the uncertainty of the derived experience curve parameters can also be substantial. When using these parameters for cost extrapolations, it is recommended to take into account this uncertainty, e.g., by presenting the confidence interval of extrapolations, or by using a stochastic model formulation of parameter uncertainty (van Sark et al. 2010).

4.1.3.2 System Boundaries and Functional Units

The definition of system boundaries, and the choice of the functional unit affects the value of the derived experience curves, and to a certain extent determines whether any reasonable experience curve can be derived at all. If technologies are aggregates of multiple components, it is fair to assume these components each have specific potential for cost reduction, and thus would have different learning rates. Using experience curves for the aggregate system would in that case overestimate future cost reductions, and a recommendation is to use either component-based experience curves (Junginger and Louwen 2020), or to devise some form of a piece-wise experience curve (Kittner et al. 2017).

A similar system boundary issue results from technologies that are in fact heterogeneous, but are normally considered as a single technology such as lithium battery electricity storage systems, which vary in materials used and their designs.

When deriving experience curves, it is important to determine the appropriate functional unit. As recent studies for e.g., wind power show (Williams et al. 2017), unit capacity prices of wind turbines and systems have gone up and down the past decade, making derived single factor experience curves for unit capacity cost nearly useless. However, many developments in the wind power industry have focused on reducing levelized cost of electricity, rather than unit capacity prices. Hence, a more useful experience curve can be derived for wind LCOE. Furthermore, capacity prices are affected by subsidies as producers take these into account to determine acceptable market prices.

4.1.3.3 Explanatory Value of Single-Factor Experience Curves

As is often mentioned, the single-factor experience curve on its own offers no explanation of the observed cost reductions, and cannot prove any causality between cumulative production and cost developments (Yeh and Rubin 2012). With multi-factor curves, this issue can be partly alleviated, although different learning mechanisms are often difficult to separate, as the proxy data used to analyze them (such as cumulative production and patent applications) often is highly correlated in growing industries. Experience curve studies should thus ideally be accompanied with a thorough examination of the reasons behind the observed cost developments.

4.2 Data Collection and Derivation of Experience Curves

In order to derive the parameters of Eq. (4.2), and the learning rate and progress ratio, historical data needs to be collected on cumulative production and cost developments of the studied technology. Commonly, especially for more mature technologies, cumulative production figures are easily collected, sometimes calculated based on cumulative sales or cumulative installation data as proxies. Productions *costs* of technologies are generally much more difficult to find however, and therefore many experience curves studies use market *prices* as proxy data. For mature technologies in a stable market, it is often assumed that market prices and production costs decline at an equal rate, but in early market diffusion stages, subsidized markets or during supply/demand imbalances, there can be significant differences between market prices and production costs (Boston Consulting Group 1970). Still, out of necessity it is often unavoidable to use market price data as cost data is not publicly available. Furthermore, this can also be justified as investments decisions in technologies are usually made based on the price, rather than production costs, of a technology.

4.2.1 Functional Unit and System Boundaries

As discussed before, the choice of the functional unit has its implications on the validity and usefulness of the derived experience curve, but it should also be aligned with the intended application of the curve. In the context of energy modeling, the curve should ideally be derived for the unit based on which the model makes investment decisions. For many electricity generation technologies, the functional unit would thus most likely be in e.g., EUR/kW of capacity, however, as was discussed before this is not possible or even useful for every technology (see e.g. wind energy).

In terms of system boundaries, it is important to clearly define the technology under investigation, and make decisions on whether to investigate technology components rather than an aggregate technology system. Examples here are PV systems, which have separate learning rates for PV modules *vs.* inverters, or battery storage systems, which are quite heterogeneous in technological design, as well as being a combination of several components with different potentials for cost reduction, hence will likely have a non-constant learning rate when analyzed as a complete system with a single learning rate.

4.2.2 Correction for Currency and Inflation

In order to derive the experience curve, it is necessary that the cost (or price) data is expressed in real terms, e.g., that is corrected for inflation using for instance a GDP-deflator (Junginger et al. 2010; Louwen and Subtil Lacerda 2020), as without this correction, the derived experience curve parameters would otherwise be affected by the rise in prices resulting from inflation. Consequently, datasets with different currencies need to be converted to a single currency.

4.2.3 Deriving Experience Curve Parameters

Experience curve parameters can be determined by performing a nonlinear regression of the untransformed data, or by a linear regression of the logarithmically transformed x and y data. Although the discussion on the best approach for experience curves is limited in literature, the consensus seems to be to perform a linear regression of log-transformed data, both within experience curve studies as in the broader scientific literature.

With the corrected empirical data on prices and cumulative production, the experience curve formula can be fitted by means of a linear regression of the logarithmized data:

$$\log C = \log C_1 + b \log N \tag{4.5}$$

Using statistical software, the values of parameters C_1 and b can be derived, including information on the errors of these parameters, their statistical significance, as well as the overall statistical significance of the overall regression. Often a coefficient of determination (R^2) is presented to show the accuracy of the fitted model, although this coefficient has its fair share of critique. Given that statistical software can also provide other goodness of fit metrics, it is recommended to also show these metrics in addition to the R^2 value.

When performing extrapolations based on the derived experience curves, it is recommended to consider the errors in the learning rate in an uncertainty analysis. Although computation time is likely prohibitive in many modeling applications, it is recommended to take into account the uncertainty of the experience curve parameters explicitly, for instance via a stochastic model formulations using the parameter errors obtained from the regression (van Sark et al. 2010).

4.3 Experience Curves in Energy System Models

Within the REFLEX project, one of the main aims was to model pathways toward transformed, low-carbon energy systems up to 2050. As the time horizon increases, the uncertainty regarding technological progress and the associated technology cost reductions becomes larger. Conventional approaches in energy system modeling are to assume an exogenous cost trajectory, uninfluenced by model developments. However, it is unlikely that cost decline occurs over time, without being influenced for e.g., by technology deployment. Therefore, the REFLEX project applied experience curves to be able to model future technology cost developments. Endogenously implemented experience curves allow for an enhanced assessment of the impacts and requirements of policy measures or other incentive schemes. Furthermore, with experience curves, the market diffusion and cost reduction of existing and new energy technologies can be modeled in a feedback loop with cost trajectories derived from experience curves.

In this chapter the technical implementation of experience curves in the various models utilized in the REFLEX project is discussed. Furthermore, several issues related to this model implementation are indicated and possible solutions are examined.

4.3.1 Model Implementation of Experience Curves

In an ideal situation, the derived experience curves are implemented directly in the modeling code, using Eq. (4.2) as shown in Sect. 4.1.1. Implementing this equation directly would allow for endogenous modeling of technology cost development. This is however not feasible for every type of energy system model. Requirements are that the mathematical layout and optimization approach is compatible with implementation of the power law curve of Eq. (4.2), and that the model's geographical scope is global, as technological learning is assumed to occur on a global scale. Alternatively, the implementation can be exogenous, where experience curves are used to calculate cost trajectories using market deployment data from well-aligned (in terms of modeling scenario) global models.

In a direct, endogenous implementation, there is a feedback loop between deployment of technologies and the experience curve. Cumulative technology deployment is given as an input to the experience curve, and the resulting cost is applied in the model in the feedback loop. If the model does not directly produce the required input data (cumulative production), if possible, a conversion from the model outputs to cumulative production can be made, serving as input for the experience curve.

In an exogenous implementation, costs are derived on a time-basis. Market deployment of installed capacities of the respective technologies is taken from an external source, ideally a global energy system or integrated model analyzing a well-aligned modeling scenario. The cumulative technology deployments from this external model are used in conjunction with the experience curve to derive exogenous, time-based cost trajectories, which are fed to the original model.

4.3.2 Issues with Implementation of Experience Curves in Energy Models

When implementing experience curves in energy models, a variety of issues can be encountered, such as inadequate geographical scope and technical model constraints. Here, several of these main issues are investigated.

Within the REFLEX energy system modeling framework, most models are limited in geographical scope. Assuming technological learning to occur at a global scale, and thus costs are a function of global cumulative production, this limited geographical scope prevents the models from being able to fully endogenously model costs using the experience curve.

A possible solution here is to derive the cumulative technology deployments for the countries outside the local model from an exogenous global model (Louwen et al. 2018). In this way, there can still be a feedback loop between costs and technology deployment in the local model. However, this means that depending on the geographical scale of the local model, the contribution to global cumulative deployments might be very limited, hence the effect of deployment within the local model on cost decline can be small. Furthermore, the global model should be compatible with this approach in terms of geographical subdivision, and should be modeling a well-aligned scenario. An alternative approach would be to determine global capacity developments fully exogenously in terms of small additions from within the local model, using for instance an S-curve approach (Fleiter and Plötz 2013; Schmidt et al. 2017).

The technical design of energy system models is sometimes also inhibitive to implementation of experience curves. Especially optimization models are not compatible with the nonlinear experience curve equation, requiring the implementation of a piece-wise approximation of the function (Barretto 2001; Heuberger et al. 2017). Also, optimization have a so-called 'perfect foresight', meaning technologies with high learning rates are preferred, while contrastingly simulation models avoid technologies with high initial costs, requiring certain incentives to push simulation models to deploy these technologies.

4.3.3 Description of Energy Models with Implemented Experience Curves

Within the REFLEX project, experience curves are implemented in the models FORECAST, ELTRAMOD, PowerACE, ASTRA, and TE3 (cf. Chapter 3). The models are linked in what is called an Energy Model System (EMS), where the outputs of some models serve as input for the other models, in several feedback iterations. In this way, the complete European energy system is modeled with high levels of technological detail and including all energy demand and conversion sectors. In the paragraphs below, these models in the context of experience curve implementation are shortly described.

Within the REFLEX project, the FORECAST model is the key model that delivers energy demand figures to the EMS. FORECAST is a bottom-up simulation model with a high level of technological detail, and is primarily aimed to support strategic decisions in the context of long-term development of energy demand and greenhouse gas emissions, and covers the industry, residential and tertiary sectors (Jakob et al. 2012; Fleiter et al. 2018). Within REFLEX, the FORECAST model applied experience curves for heat pumps and alkaline electrolysis (Schreiber et al. 2020 and cf. Chapters 6 and 7), in a semi-endogenous manner, using a combination of technology deployment from within the model and technology deployments from an external integrated assessment model. These two technologies are seen as the most potential appliances for decarbonizing energy demand from buildings and industries.

ELTRAMOD, short for ELectricity TRAnsshipment MODel, is a bottom-up optimization model aiming to model cost-minimal investments and dispatch of electricity generation facilities, including storage and power–to–x technologies (Zöphel et al. 2019; Schreiber et al. 2020). The model covers all EU–27 member states, and additionally includes Norway, Switzerland, United Kingdom, and the Balkan countries.

Since ELTRAMOD is an optimization model and is not compatible with the nonlinearity of the experience curve function, a procedure was developed to implement experience curves using a piece-wise approximation of the experience curve. However, the implementation of experience curves using this approximation induced significant increases in computation time, hence, given the multi-iterative modeling schedule of the REFLEX EMS, it was opted to include the experience curve data exogenously. In ELTRAMOD, the exogenous experience curves were implemented for carbon capture and storage equipped at a variety of electricity generation technologies, for utility scale battery storage systems (lithium-ion and redox-flow), for heat pumps, and for alkaline electrolysis (cf. Schreiber et al. 2020 and Chapter 10).

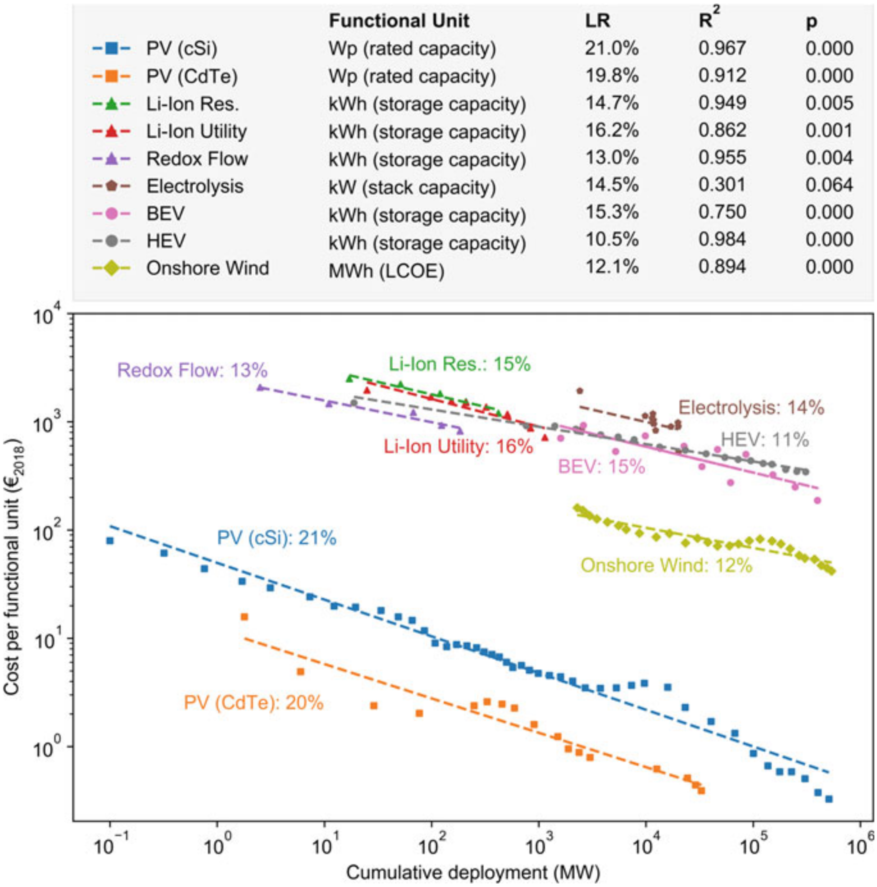
PowerACE is a bottom-up and agent-based simulation model that analyzes impacts of market design and policy measures on deployment of low-carbon technologies (cf. Fraunholz et al. 2020 and Chapter 11). Electricity generation companies and other electricity market actors are modeled as individual agents, including electricity demand and generation from renewable resources. The focus of the model is thus the electricity market, supply and demand on a high time-resolution, but investments in generation and storage capacity are also included and are planned in the model on an annual basis (Fraunholz and Keles 2019; Fraunholz et al. 2019). Given the limited geographical scope of the model, experience curves for PowerACE, are implemented exogenously for utility scale electricity storage (lithium-ion and redox-flow batteries) and electricity generation with CCS (Schreiber et al. 2020).

ASsessment of TRAnsport Strategies (ASTRA) is a system dynamics model aimed to provide strategic policy assessment in transport and energy. It covers all EU-27 members, and additionally includes Norway, Switzerland, and the United Kingdom (Fermi et al. 2014 and Chapter 7). ASTRA focuses on passenger and freight transport, including all forms of transport (road, rail, air, and water) and the active modes cycling and walking. It models the development of transport per mode, and can report a variety of indicators like fuel consumption and greenhouse gas emissions. Market diffusion of vehicle technologies is modeled based on a total cost of ownership (TCO) approach that considers among others vehicle prices, fuel or energy prices, and maintenance. In ASTRA, experience curves are implemented for the battery pack component of battery, plug-in hybrid and fuel cell electric vehicles. Although the geographical scope of ASTRA is not global, experience curves are implemented endogenously, as global market developments are supplied by another transport model within the REFLEX EMS, the global model TE3 (Heitel et al. 2020).

The Transport, Energy, Economics, Environment (TE3) model is the final model discussed here. TE3 models passenger road transport, is also a system dynamics model, and is used for policy analysis. It includes all major non-European markets like India, Japan, China, and the United States (Gómez Vilchez and Jochem 2019 and Chapter 5). Technology choice is influenced by several parameters including social dynamics, policy measures, and (available) infrastructure, and technology cost. Like in ASTRA, experience curves are used endogenously in TE3 to model the costs of the battery pack components of battery, plug-in hybrid and fuel cell electric vehicles.

4.4 State-of-the-Art Experience Curves and Modeling Results

Within the REFLEX project, experience curve data was collected for a diverse set of technologies. An overview of the result for selected key technologies is given in Fig. 4.3. For all technologies listed, costs per functional unit are plotted against cumulative installation of each technology in MW.



	Functional Unit	LR	R^2	p
-■- PV (cSi)	Wp (rated capacity)	21.0%	0.967	0.000
-■- PV (CdTe)	Wp (rated capacity)	19.8%	0.912	0.000
-▲- Li-Ion Res.	kWh (storage capacity)	14.7%	0.949	0.005
-▲- Li-Ion Utility	kWh (storage capacity)	16.2%	0.862	0.001
-▲- Redox Flow	kWh (storage capacity)	13.0%	0.955	0.004
-⬟- Electrolysis	kW (stack capacity)	14.5%	0.301	0.064
-●- BEV	kWh (storage capacity)	15.3%	0.750	0.000
-●- HEV	kWh (storage capacity)	10.5%	0.984	0.000
-◆- Onshore Wind	MWh (LCOE)	12.1%	0.894	0.000

Fig. 4.3 Overview of experience curves for selected technologies. *Data sources* according to Schmidt et al. (2017), Williams et al. (2017), Louwen et al. (2018), Junginger and Louwen (2020). LR = learning rate. The *p*-values indicate the *p*-value for the F-test of overall significance of regressions

4.4.1 Overview of State-of-the-Art Experience Curves

For PV modules, both crystalline silicon (cSi) and cadmium telluride (CdTe) based, learning rates of around 20% are observed, while for other technologies much more varied learning rates were found. Clearly observable in the dataset for PV (cSi) module prices, is a period of price stability, even a small increase in prices around installed capacity of 100 GW. This deviation from the overall experience curve trend was the result of a sharp increase in silicon prices, resulting from a shortage in silicon production. Subsequently, when silicon production capacity was greatly expanded and silicon prices declined rapidly, a sharp decline of PV (cSi) module prices occurred.

For heat pumps, learning rates of around 20% for the total system were observed, based on data from Switzerland, while the learning rate for the specific cost of energy supplied is in the range of 20-25% due to improvements in the technical performance of heat pumps (Jakob et al. 2020). Although the empirical basis for heat pump experience curves needs to be improved, the high learning rates observed indicate the potential for heat pumps to become cost competitive with natural gas boilers (Jakob et al. 2020).

For alkaline electrolysis, a learning rate of 14.5% is detected, although the spread of data points results in a low goodness of fit, with a poor R^2 and a p-value of 0.064, indicating the regression is not significant at a confidence level of 0.05. For all other technologies, the regression was found to be significant at this confidence level.

For both utility scale and residential storage systems (respectively, Li-Ion Utility and Li-Ion Res) and for battery electric vehicle (BEV) battery packs, learning rates of around 15% are observed, while for hybrid electric vehicle (HEV) batteries, the learning rate was found to be much lower, at 11%. For BEV battery packs, significant variance is present in the dataset, leading to a relatively low R^2 value.

For onshore wind, the data of Williams et al. (2017) are analyzed, which represents levelized cost of electricity (LCOE) for onshore wind systems, in a model that corrects for a variety of parameters, including wind quality of the wind farms that are included in the dataset. A learning rate of 12% is observed for LCOE as a function of cumulative production, although when the LCOE data is expressed as a function of cumulative electricity generation (rather than cumulative capacity), a higher R^2 value is obtained, as this also includes a correction for the increase in capacity factors that are observed over time.

The interested reader is referred to Louwen et al. (2018), where detailed results of the project regarding the learning curve approach are presented.

4.4.2 Deployments and Cost Developments of Relevant Technologies

Within the REFLEX project, experience curves have been implemented for a number of technologies. An overview of these technologies is given in Schreiber et al. (2020) and Heitel et al. (2020). In this section the diffusion of key technologies in the different models described above and in Chapter 3 are discussed, and cost trajectories for these technologies are presented.

Transport technologies are modeled within REFLEX with the models ASTRA and TE3. To ensure consistent diffusion of vehicle types, and since the geographical scales of the models are different, market diffusion of transport modes is aligned in the two models in the REFLEX model coupling system (Heitel et al. 2020). The model results (Heitel et al. 2020) indicate that EV battery prices decline to 89 EUR_{2018}/kWh in 2030 and 59 EUR_{2018}/kWh in 2050, down from prices of around 300 EUR_{2018}/kWh in 2015, the starting year of the transport models, with cumulative global deployment of EV batteries (89% outside of the EU) approaching 30 TWh in 2050. As expected, the sensitivity analysis shows that especially the uncertainty in the derived learning rates can significantly affect the deployment of EVs. Lower learning rates result in a slower cost decline of vehicle prices, which in turn slows the diffusion of EVs, while with higher learning rates, costs decline faster and market diffusion is also sped up.

Within ELTRAMOD, the optimization model of electricity generation facilities, experience curves are applied exogenously to determine cost developments for battery storage, CCS and power-to-x technologies. As the cost trajectories are thus independent of technology deployment within different modeling scenarios, it is more interesting to discuss sensitivities of these cost trajectories to the applied learning rates. This sensitivity analysis shows that as higher learning rates are assumed for battery storage systems, the deployment of these technologies is increased. This furthermore influences the deployment of other technologies such as CCS and CCGT, which show slightly reduced investments. Similar results are obtained in PowerACE, where impacts of market design and policy measures on deployment of low-carbon technologies are modeled: high learning rates for battery storage systems result in strongly increased deployments of these technologies at the expense of deployments in CCGT and OCGT generation and a strong reduction of deployments of compressed-air energy storage.

Within FORECAST, technological learning is considered for several energy demand technologies. However, since FORECAST is actually a group of models describing different demand sectors separately, an iterative approach was applied to make sure technology deployments in one sector can influence technological learning in the other sectors and vice versa (Schreiber et al. 2020). Heat pumps represent a key technology in the heat demand sector in future energy scenarios, and for this technology a cost reduction of around 20% was observed up to 2050, compared to the minimal cost reductions examined without considering technological learning. However, it was found that the installation rates of especially heat demand technologies were less affected by cost developments and technological learning, and were to a larger extent the result of scenario constrains (Schreiber et al. 2020). As the technology cost of heat demand technologies only represents a minor share in overall heating systems costs in terms of building refurbishment and the cost differences between different heating technologies are small, energy price differences or the cost for building refurbishment measures have a higher impact on the overall cost structure (Harmsen et al. 2017).

4.5 Lessons Learned

As illustrated in this chapter, a comprehensive effort was undertaken to collect data with which state-of-the-art experience curves could be derived and to implement these experience curves in a variety of energy models that are part of the REFLEX Energy Modeling System. Particular effort was devoted to the endogenous implementation of experience curves in the models which was not as straightforward as was anticipated. The main lessons learned during this research are briefly discussed below.

4.5.1 Methodological Issues

Regarding general methodological issues, some limitations of the experience curves were identified. These relate to the defined technology system boundaries and functional unit of the experience curve, but also to exogenous parameters affecting cost developments of technologies. Multi-factor experience curves can be a valuable extension of the single-factor experience curves adopted in the REFLEX project, giving the possibility to include the effects of additional parameters such as R&D activities, commodity prices, and market dynamics. While these multi-factor experience curves could offer the opportunity to attain more accurate cost modeling results, further research is required to make a good comparison between single- and multi-factor experience curves, and to study model implementation of multi-factor experience curves, since model implementation of this type of experience curves is much more complex. Further research should thus investigate the optimal balance between the improved accuracy of results *vs.* the added modeling complexity.

An issue related to system boundaries and functional units is the topic of component-based experience curves. For several technologies evidence are identified that components of the technology system have different learning rates. To accurately represent the cost developments of these technologies on the long term, experience curves for the separate components should be implemented to avoid overestimation of future cost reductions. By using component-based experience curves, the issue of spillover effects across different industries could also be at least partly addressed. Especially for lithium-ion batteries, which are used in electronics, in residential and utility scale stationary electricity storage and in electric vehicles, a key recommendation is to investigate experience curves of the different components from battery cells to energy-management systems, although data availability might be prohibitive. As a matter of facts, the model implementation of such component-based experience curves, especially multi-factor version of them, drastically increases the complexity and the requirements of the model to produce input data for the experience curves, making further research on this topic a necessity.

4.5.2 Model Implementation Issues

With regard to model implementation, one main issue is how to represent technologies for which there is a lack of empirical data due to their implementation readiness. For early stage technologies like carbon capture and storage (CCS), or energy storage types with small implementation numbers such as compressed-air energy storage, there is almost no empirical data that allows for the derivation of experience curves. This means that the cost developments of these technologies in energy modeling need to be represented either by using experience curves based on proxy technologies, or by some exogenous cost estimations. For high profile technologies like battery-based electricity storage, the available datasets that allow for derivation of experience curves are quite limited in terms of timeframe, hence there is little certainty on the long-term cost developments of these technologies. The implications of this with regard to modeling results should be explicitly discussed, especially in those cases, like the REFLEX project, where the analysis goes up to 30 years ahead. Therefore, a key recommendation is to focus on the creation of cost (and not price) databases that track the costs of these kinds of technologies, for instance by ensuring the assessment and publication of cost data for publicly supported pilot projects for CCS and other novel technologies.

Another theme related to the model implementation of experience curves is the geographical scope of the respective energy model, which is often limited. Assuming technological learning is a global process, some form of exogenous cumulative production data is required. This can be derived through a variety of approaches, such as by using results from external global models that analyze well-aligned scenarios, or alternatively by using the S-curve based approach. Within the REFLEX project, a combination of these measures was applied on a more or less ad hoc basis. Future research projects that aim to implement experience curves in a similar manner in geographically restricted energy models, should outline an explicit approach to deal with this problem, for instance by including a global energy or integrated assessment model in the modeling activities, ensuring a consistent scenario analysis across global and regional models.

There were also several technical issues identified with regard to model implementation. A typical problem is the fact that the power curve function of experience curves is not compatible with some models, requiring the implementation of a piecewise linear approximation of the original function. Also, models tend to have either perfect foresight (optimization models) or contrastingly, a myopic view (simulation models), which could result in over- or underrepresentation of technologies in the modeling outcomes. Finally, it was found in the REFLEX project that the modeling scenarios that are investigated can also be a barrier for the implementation of experience curves for certain technologies; this is the case where technology deployments are defined as scenarios inputs, for instance by means of targets for the deployment of renewable energy technologies.

4.6 Conclusions

A final recommendation is to further develop research studies on applications of experience curve and technological learning mechanisms outside the economy sector. As part of the REFLEX project scientific literature review, several studies were identified that use experience curve to describe developments in energy efficiency of appliances and industrial processes (Jakob and Madlener 2004; Ramírez and Worrell 2006; Weiss et al. 2010; Brucker et al. 2014; Fleiter et al. 2017) as well as greenhouse gas and energy demand of renewable energy technologies (Bergesen and Suh 2016; Louwen et al. 2016). Furthermore, the concept of technological learning has been applied in the domain of social sciences to represent the effects of *social learning* on the market diffusion of battery electric vehicles (Edelenbosch et al. 2018). It would be therefore extremely interesting to expand the scope of application of experience curves in energy modeling so as to allow for the endogenous modeling of these additional parameters.

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Chapter 5
Electric Vehicle Market Diffusion in Main Non–European Markets

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Abstract Electric vehicles (i.e., battery and plug-in hybrid electric vehicles) are seen as one promising technology toward a sustainable transport system as they have the potential to reduce CO_2 emissions. The forecast of their market penetration depends on various factors including the cost development of key components such as the electric battery. This chapter focuses on the impact of experience curves on the battery costs, and consequently on the electric vehicles' market penetration, which is simulated by coupling two system dynamics transport models: ASTRA, representing Europe, and TE3, representing key non-European car markets. The results of the TE3 model show that the consideration of global endogenous learning curves has an impact on the battery costs and therefore, the development of the electric vehicle stock ("feedback loop").

5.1 Introduction

5.1.1 Motivation

The transport sector has not yet contributed to greenhouse gas mitigation targets but increased its emissions in most countries. As user behavior stayed rather constant during the last decades and a further increase in motorized transport is being observed—mainly in developing countries—technological solutions come into the focus for enabling the transition toward transport sector decarbonization. Hence, electric vehicles (EV) (including battery EV (BEV) and plug-in hybrid EV (PHEV)) in combination with the already ongoing energy transition seem to be a possibility to reverse the increasing trend of producing greenhouse gas emissions even if the number of the global passenger car fleet might double until 2050 (Creutzig et al. 2015).

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In the vein of this book chapter this increase in EV registrations has two effects. Due to the increase in battery demand, learning effects (cf. Chapter 3) will lead to decreasing battery prices. This effect reduces the price of stationary storages for the electricity system and the prices for new EV, which in turn accelerates their market penetration and increases the flexibility of electricity consumption. The consideration of global battery demand is necessary for modeling this effect adequately as batteries are produced and traded internationally.

5.1.2 Related Research and Research Question

Until now, mobile information and communications technology devices such as smart phones and laptops have dominated global battery demand. If the EV market gains momentum, the battery market will experience a tremendous acceleration. Hence, the development of global EV registrations over time is decisive and should be carefully analyzed.

In literature there is already a plenitude of studies which deal with this future market and show the related high uncertainties (Gnann et al. 2018). Also the variety in the underlying methods is manifold (Jochem et al. 2017). Many studies have a shorter time horizon than 2050 (IEA 2018; Tsiropoulos et al. 2018). Most studies focus on one dedicated market (e.g., on Japan in González Palencia et al. 2017 or on China in Liu and Lin 2017) and do therefore neglect the global feedback effect (i.e., each local market of EV is dependent on the price development of batteries, which are mainly resulting from the global EV production). Hence, global scenario analysis is a suitable approach to analyze these uncertainties of future markets. For Europe suitable studies already exist (cf. Chapter 7 or Pasaoglu et al. 2016). However, considering additionally the non-Europe countries and therefore a model coupling in particular is still underrepresented in the literature. Consequently, the research question of this section is on how the EV market develops over time in the main non-European car markets within our given scenario framework. These four countries (US, Japan, India, and China) were chosen as they have over 60% of global car sales in 2016 (OICA 2018) and are expected to have over 30 million EV in the next years as they are members of the EV Initiative and thereby showing public commitments toward the EV deployment (EVI 2016).

The structure of the chapter is the following. Section 5.2 presents a discussion on the development of EV, including the implementation of the experience curve in existing transportation models to foster global learning as well as the defined scenario framework. Section 5.3 outlines the results and discusses limitations and Sect. 5.4 concludes and sums up the chapter insights.

5.2 Considering Experience Curves in Market Diffusion Modeling and Scenario Definition

5.2.1 The TE3 Model and Implementation of Experience Curves

The TE3 (Transport, Energy, Economics, Environment) model supports policy-making analysis in the context of oil demand reduction and GHG mitigation from car travel (Gómez Vilchez 2019).[1] This tool explores market developments of future car powertrain technologies and offers an international perspective by covering six main car markets. The time horizon is limited to the period from 2000 to 2050 and the underlying methodology is mixed, as the model contains elements of econometrics and system dynamics (SD).

The endogenously implementation of experience curves of batteries for EV in the TE3 model is based on SD core concepts, considering feedback loops as well as distinguishing between flow and stock variables (see e.g. Sterman 2000). For the implementation of the experience curve in the TE3 model the following Eq. (5.1) is used.

$$C(X) = C_0 \cdot X^{\log_2(1-l)} \tag{5.1}$$

The parametrization of this Eq. (5.1) is derived from Chapter 4. The battery costs *C(X)* result from the product of the battery costs in the first year C_0 and the overall production of batteries X as well as the learning rate l (15.2%) and is measured in USD/kWh. The cumulated battery capacities include BEV and PHEV batteries with their assumed battery capacities of 30 kWh and 10 kWh per car, respectively. While the historical costs are taken from literature, the overall production of batteries relies on the EV stock of the previous modeling period. This includes results of TE3 for the non-European (i.e. China, India, Japan, and US) as well as of ASTRA for the European markets. In an iterative process, the coupled models add the battery capacities of the EV in countries considered by the other model to their cumulative production; i.e., the TE3 model provides the cumulative battery capacities of the considered non-European markets and ASTRA of the European markets. This may lead—according to the learning curve approach (cf. Eq. 5.1)—to adjusted battery costs, which in turn may influence the EV market penetration of new model runs of the two models. This iterative process represents the so-called “feedback loop” (cf. Chapter 3). In this way, the development of the European market as well as of the four key non-European ones is jointly considered. Through the implementation of the respective experience curves and the described linkage between the two transport models, the global development of the battery costs is modeled endogenously.

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[1] A version of TE3 is available at www.te3modelling.eu and further details can be found in Gómez Vilchez (2019).

5.2.2 Framework of the Two Analyzed Scenarios for the Main Non-European Car Markets

Many EV specific policies have been launched over the last years. Recently, some countries even announced sales bans for internal combustion engine vehicles (ICEV) (e.g. IEA 2017a; Plötz et al. 2019). As part of the REFLEX modeling framework, one Mod-RES and one High-RES scenario is introduced. In the High-RES scenario it is further distinguished between a centralized and decentralized world (cf. Chapter 2). For the four non-European countries the distinction between a centralized and decentralized world is not considered.

The implementation of the two developed scenarios (Mod-RES and High-RES) to the BEV case is outlined in the following, including assumptions with respect to the applied EV policy and the general development of the respective countries with respect to population and resulting overall passenger car stock. The Mod-RES scenario relates in principle to current policies and the High-RES scenario until 2030 as well. The latter includes a higher investment in infrastructure and lower emission standards and has therefore, a stronger EV increase. Both scenario represent possible outcomes, knowing that until 2050 there is a high uncertainty.

5.2.2.1 Mod-RES Scenario

The current policy instruments aiming at sustaining EV diffusion in the US, Japan, China, and India resemble each other in main points.

Table 5.1 gives an overview over most of the support programs for EV. Each of these countries gives a tax break or another financial incentive on the purchase price of EV. Japan exempts quite many taxes for owners of an EV (e.g., acquisition tax and tonnage tax). All countries subsidize the charging infrastructure by providing attractive loans or by directly co-financing charging stations. Non-financial incentives are quite common in China and the US: EV users have a clear advantage over others while driving exclusively on specific lanes such as bus lanes or have access to dedicated inner-city areas. In the US, incentives may vary from state to state. California is the state where EV owners receive significant advantages due to the Clean Vehicle Rebate Project and the State's government has a challenging goal to reach five million EV in 2030 (Clean Vehicle Rebate Project 2019). With the "Energy Independence and Security Act of 2007" the US support the expanding, establishing or equipping manufacturing facilities in the US with direct loans to increase the production of clean renewable fuels (US Congress 2007). The US supported automobile manufacturers with already eight billion USD (Tesla, Ford, and Nissan) out of this loan program whereas 17.7 billion USD are still remaining (US Department of Energy 2019a). China makes clear requirements for all car manufacturers which sell cars in China. This includes fines if they do not produce a certain number of EV (Environmental and Energy Study Institute 2018). Furthermore, they focus on dedicated EV shares in overall sales. In India, the government tries to reduce dependency on oil

Table 5.1 Considered support programs for electric vehicles

	Goal	Financial incentives	Charging infrastructure	Non-financial incentives	Requirements/incentives for manufacturers	References
India	2020: 7 million EV of total car stock 2030: all new cars sales should be EV	FAME INDIA II 1.2 billion USD, 100,000₹ for subsidies to electric- buses, four-wheelers (EV, PHEV, HEV), three-wheeler and two-wheelers; 10,000₹ (140 USD) for each kWh of battery capacity	FAME INDIA II 140 million USD	–	–	National Automotive Board 2019
China	2020: 2 million EV; 2025: 20% of all car sales	Release from purchase tax subsidies (up to 66,000 RMR, 8,500 EUR)	Subsidies for local governments for charging stations by 2020; Could receive up to 14 million USD to install EVSE if aspects like reaching a certain amount of EV purchases are fulfilled	Awarding license plates (chances are higher obtaining a license plate through lottery); Driving ban days (no driving bans for EV)	Corporate average fuel consumption; Certification to obtain a EV manufacturing license	Environmental and Energy Study Institute 2018, IEA 2017b
Japan	2020: 20-30% of all cars sales	Subsidies (up to 850,000 JPY (~ 6,450 EUR); Exemption from the acquisition tax and tonnage tax; 50% of the annual automobile tax	Subsidies for DC charging points up to 60% of the total cost	—	—	IEA 2017a

(continued)

Table 5.1 (continued)

	Goal	Financial incentives	Charging infrastructure	Non-financial incentives	Requirements/incentives for manufacturers	References
US	2015: 1 million EV (Sep. 2018 achieved); State specific goals e.g. California (5 million EV in 2030)	Federal tax credit: 2,500–7,500 USD	Improved Energy Technology Loans	In many states, BEV und PHEV have access to the carpool lane; Inspection exemptions in some states	Advanced Technology Vehicle (ATV) and Alternative Fuel Infrastructure Manufacturing Incentives; overall 25 billion USD planned	US Department of Energy 2019a, 2019b

imports and promote the adoption of alternative fuels through introducing the FAME (Faster Adoption and Manufacturing of Hybrid and EV) initiative. The assumption of a strong EV increase in India until 2030 is not included as the planned values are not fixed values by now. ICEV selling bans are not considered in any of the four key non-European countries in our modeling because it is not clear whether the policy will remain until that period.

The Mod-RES scenario is in principle related to these rather short-term policies like subsidizing charging infrastructure. As it is hard to tell how to extrapolate the policies until 2050 the assumptions were more restrained, e.g., no further purchase subsidies were assumed. In general this scenario shows one possible future development pathway for the different car technologies.

When it comes to the population development of the four considered countries the medium variant scenario of the United Nations is taken until the year 2050 (cf. United Nations, Department of Economic and Social Affairs, Population Division 2017). Accordingly, China's population increases until 2030 and decreases afterwards. Japan has an overall decreasing trend. India and the US are assumed to steadily increase their population numbers (cf. United Nations, Department of Economic and Social Affairs, Population Division 2017).

To assess the total car stock, car ownership ratios are assumed. China is the country with the strongest increase for this ratio, having in 2018 about 11% of car ownership (i.e., 110 passenger cars per 1,000 inhabitants). It is assumed to be at around 31% (i.e., 310 passenger cars per 1,000 inhabitants) in 2050. While also for India and Japan a positive trend of this ratio is expected, the US car ownership ratio is assumed to be stable. Back in 2015, China had still a car stock of 136 million passenger cars and India about 22.5 million passenger cars (OICA 2018). Hence, both car stocks will increase significantly over the next period.

5.2.2.2 High-RES Scenario

While population and car stock have the same values as in the Mod-RES scenario, an even stronger increase in the charging infrastructure is assumed for the High-RES scenario as one policy measure. Different studies present various development plans for EV charging infrastructure in a range of eight million of up to 33 million units in 2030 for the whole world (cf. IEA 2017b). In comparison, one further assumption is that in the High-RES scenario ten million EV supply equipment (EVSE), i.e., charging stations, are installed by 2030, leading to about 33 million for 2050 for the four considered countries. According to the German National Platform Future of Mobility this is still a rather unsatisfactory low number because one EVSE outlet for 15 EV (i.e., 10 million EVSE per 150 million EV in 2030) might not provide a seamless operation of EV. Additionally, the average emission standards for new cars amount to 40 g CO_2/km in 2050, whereas the values of the Mod-RES scenario are assumed to be 50 g CO_2/km in 2050.

5.3 Results of Key Non-European Countries

5.3.1 *Effects on Cumulative Battery Capacity and Battery Costs*

Figure 5.1 presents the development of the cumulated battery capacity (solid lines) and the derived battery costs (dotted lines) for the four key non-European countries and Europe (provided through the ASTRA model, cf. Chapters 6 and 7) in the time span from 2015 to 2050 for the Mod-RES and High-RES scenarios. While initially both scenarios develop very similarly, there is a significant increase of the cumulated battery capacity after the year 2030 in the case of the High-RES scenario.

The development of the battery costs well reflects the learning curve behavior with a significant decrease by about 50% in 2030 and up to 70% in 2050 compared to the year 2020. It can be seen that in both scenarios the shape of the curve is similar and the battery costs differ in 2050 by only 4 USD/kWh. The battery costs of 68 USD/kWh in 2050 represent 18% of the costs in 2015; this is due to the development of cumulated battery capacities, which is driven by EV volumes.

The development of battery costs is analyzed in several studies. The spread of the costs varies from 40 EUR/kWh to 250 EUR/kWh by 2040. Most of the studies depict battery costs between 50 and 100 EUR/kWh in the long-term, in particular if they were conducted after 2015 (cf. Tsiropoulos et al. 2018). Hence, the values of the two considered scenarios in this book chapter (64 USD/kWh and 68 USD/kWh in 2050) are within this range.

Different studies for the development of the EV fleets show prospects ranging from 5 TWh up to 36 TWh for the global cumulated battery capacity in 2040 (Tsiropoulos

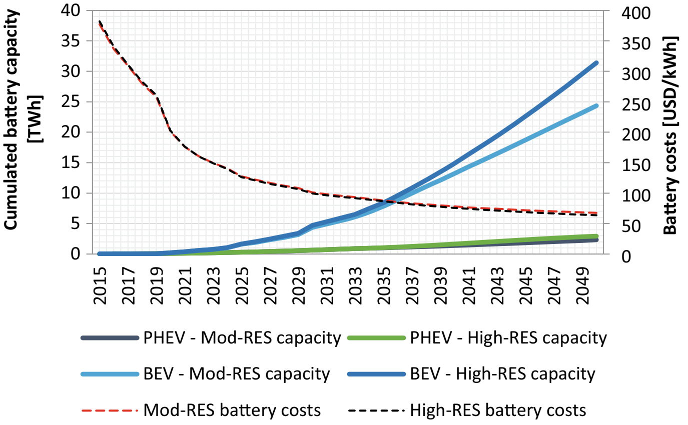

Fig. 5.1 Development of cumulated battery capacity (solid lines) for Europe and the four non-European key-countries and battery costs (dotted lines) from 2015–2050 (*Source* Figure based on data according to own calculations)

et al. 2018). In the two scenarios, the cumulative battery capacities including all the sales up to then sum up to 14.6 TWh and 16.5 TWh in 2040, respectively. In the year 2050 values of about 26.7 TWh and 34.3 TWh are reached. It should be kept in mind that the first cumulated GWh was reached in the year 2011 and the first cumulated TWh in 2015.

5.3.2 Development of the Car Stock for the Four Main Markets in the Mod-RES and High-RES Scenario

The resulting EV car stocks of the European and the four key non-European car markets increase in both scenarios from less than ten million EV to about 450 million EV (cf. Figure 5.2). The results of the Mod-RES scenario show around 80 million PHEV and 367 million BEV in 2050. If we combine the values with Europe, the numbers add up to 536 million EV. The most dynamic countries are China (211 million BEV) and India (109 million BEV). This dynamic is mainly driven by the significant incentives for investing in BEV rather than in PHEV. Consequently, the overall PHEV share is rather low. The highest national shares for PHEV are seen in Japan (17%) and the US (13%) of the overall car stock in 2050. The car sales ratio per year is in each country by at least 35%, except for the US (27%) in 2030. In 2050, each of the countries has sales values reaching from 40% (US) to 63% (China).

In the High-RES scenario the share of the PHEV drops even further to 55 million PHEV and the share of BEV increases to a value of 481 million BEV in 2050. Together with Europe, there are around 710 million EV by 2050. None of the four countries has a two-digit percentage for the PHEV penetration by 2050. The highest

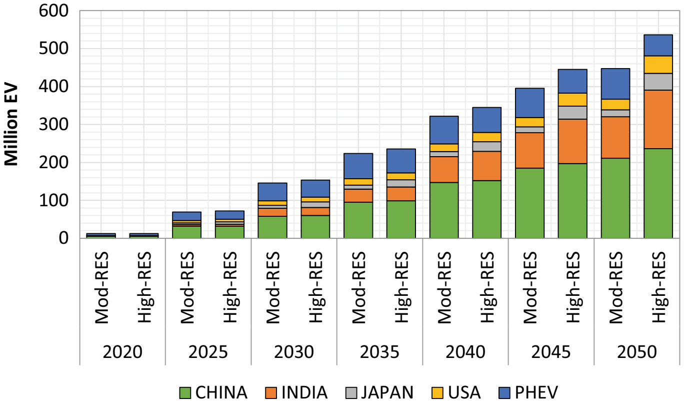

Fig. 5.2 Development of PHEV and country-specific BEV stock in key non-European car markets until 2050 for the Mod-RES and High-RES scenarios (*Source* Figure based on data according to own calculations)

share of BEV in 2050 will be in China with around 56% and the lowest one will be in the US with about 32%.

As mentioned above the main difference between the two scenarios is the higher investment in infrastructure in High-RES. Therewith the public charging infrastructure has a density of at least one EVSE outlet for 15 BEV. Apart from that, in particular the strong decrease of the battery costs to less than 100 USD/kWh by 2030 (cf. Figure 5.1) has a major impact on the increased overall penetration of the EV stock.

The EV share of the total car stock until 2050 is shown in Fig. 5.3. Car ownership ratio increases in China, Japan and India while it is quite stable in the US. The growth of the total car stock in the US is a result of the increasing number of inhabitants, which has a change from 320 million people in 2015 to 390 million inhabitants in 2050 forecasted (cf. United Nations, Department of Economic and Social Affairs, Population Division 2017). In contrast, the drivers in China and India are high shares of EV by 2050 (56 and 54%, respectively), particularly in the Mod-RES scenario.

For the High-RES scenario each of the EV shares increases, in particular the one for Japan. The modest development of BEV in the US has mainly two reasons: First, the higher purchase prices of EV compared to other countries (cf. the New Policies Scenario by the World Energy Outlook 2017). Purchase prices of EV will not undercut the one from ICEV in the US before 2025 (cf. IEA 2017a). The lower operating costs do still attract some, but not all customers. Second, not all member states in the US have announced strong EV plans. Therefore, the resulting market share of about 1/3 in 2050 of the total stock seems to be in line with other scenarios in literature.

The Mod-RES and High-RES scenarios are within the range of several other studies focusing on the development of EV until 2030 and 2040 (cf. Figure 5.4).

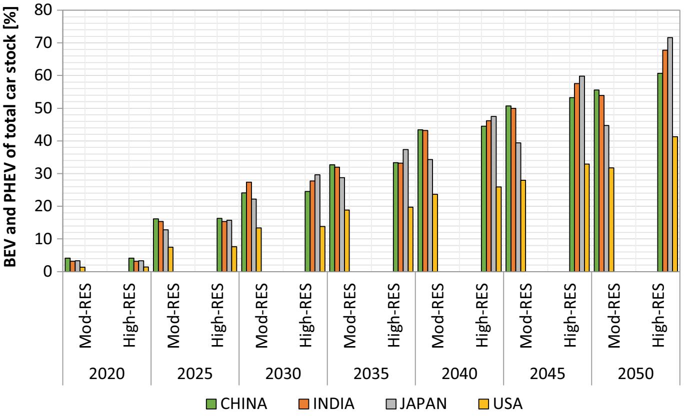

Fig. 5.3 EV share of the total car stock until 2050 for the Mod-RES and High-RES scenarios (*Source* Figure based on data according to own calculations)

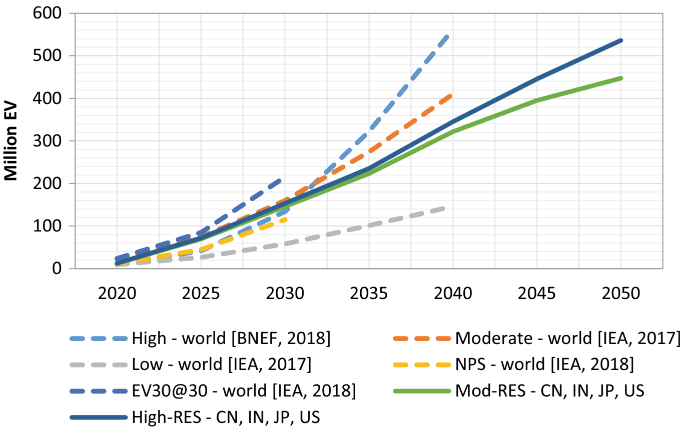

Fig. 5.4 Comparison of the global EV stock development to the four key non-European car markets of China (CN), India (IN), Japan (JP), and the US (*Source* Figure based on data according to own calculations (solid line) and for the dotted lines data from the studies of BNEF (2018), IEA (2017), IEA (2018))

Nevertheless, a “rest of the world” factor would need to be included when comparing the REFLEX scenarios to global studies such as the one of the IEA which includes other countries like Russia, Canada, Thailand, or even continents like South America or Africa that will play a role by 2050 and have a total car stock of over half a billion cars.

5.3.3 Critical Review and Limitations

Finally, some limitations should be addressed. First, the considered time period until 2050 is very long for such new technologies resulting in a lot of uncertainties. For instance, policy instruments can have a significant impact on market development in particular purchase subsidies, taxes or car bans. In this work sales bans for ICEV were not considered, however, this might have a major effect on the market diffusion of EV or other alternative powertrain technologies. The user behavior, including a change in the customer preference might be another factor, which needs to be reflected. Apart from that, factors influencing the car price, like fuel costs or resources for EV, can have an impact on the car stock as well.

Moreover, both assumed scenario developments for the non-European countries are close to each other and a stronger investment in the charging infrastructure could increase the ramp up of EV even further. Moreover, the effect of the European countries on the global learning and hence the battery costs is in comparison much smaller than the effect of all the non-European countries due to the EV numbers.

For the Mod-RES scenario the values are for Europe 85 million EV and for the non-European countries 447 million EV.

A consideration of a "rest of the world" factor would increase the accuracy of the results. Furthermore, the average learning rate (of 15.2%) was chosen for the application. A change in that parameter has a significant impact. If sensitivities of ± 2.9% are considered, the range of the battery costs is between 128 USD/kWh and 40 USD/kWh (lower and higher learning rate, respectively) (cf. Heitel et al. 2020). Moreover, a variation in the experience curve parameters would directly have an impact on the battery cost estimate and hence, on the estimated deployment of the EV stock.

5.4 Summary and Conclusions

This chapter outlined the development of EV until 2050 in four key non-European car markets (i.e. China, India, Japan, and the US). In both underlying scenarios, a significant increasing trend for the EV car stock can be seen resulting in total numbers of 447 million (Mod-RES) and 536 million (High-RES) EV for the four considered non-European markets in 2050. The PHEV share in the High-RES scenario is lower than in the Mod-RES scenario for all countries and the BEV shares have an increasing trend over time and between scenarios. Not surprisingly, China and India are seen as the main EV markets due to their ambitious policy goals.

The coupling of the two models, ASTRA (for the European market) and TE3 (for the main non-European car markets), in order to consider 34 countries in detail (and therewith more than 90% of current EV sales) allows analyzing the interrelations of global battery costs and the individual market shares endogenously. The battery costs drop from 380 USD/kWh in 2015 to below 100 USD/kWh by 2030 and decrease to values of 68 USD/kWh and 64 USD/kWh in 2050 for the two scenarios, Mod-RES and High-RES, respectively.

For further research, additional countries and policies like sales bans, higher CO_2 standards or higher investments for EVSE might be included in the modeling.

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Part III
Demand Side Flexibility and the Role of Disruptive Technologies

Chapter 6
Future Energy Demand Developments and Demand Side Flexibility in a Decarbonized Centralized Energy System

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Abstract European final energy consumption mainly stems from five sectors: transport, households, industry, residential, and agriculture using fossil fuels as dominant energy carriers. In order to achieve the climate targets, emissions in the demand sectors must be drastically reduced. Due to different characteristics and challenges each sector needs its own strategy how to achieve such decarbonization until 2050. In the following chapter, the impacts of an ambitious mitigation scenario on future energy demand and CO_2 emissions for transport, industry, residential, and tertiary are analyzed discussing sector specific decarbonization strategies and mitigation options. Implications of such strategies for demand-side flexibility and its future need are analyzed.

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6.1 Introduction

European final energy consumption can be divided in five main sectors: transport, households, industry, residential, and agriculture. The transport sector accounts for 31% of EU final energy demand followed by the residential sector with 27%, the industry sector with 25% and the tertiary sector with 15% of final energy consumption in the year 2017. The dominant energy carriers currently used are oil & petroleum products (37%), natural gas (23%), and electricity (23%) as well as renewable energy sources & biofuels (10%) (Eurostat 2017). Within the sectors the energy carrier mix varies depending on the structure and the specific requirements of the sectors. Transport energy demand is substantially dominated by fossil fuels (oil, petroleum, and natural gas) covering about 95%, with minor use of biofuels (4%) and electricity (1%) (European Commission 2017). Residential demand mainly stems from residential heating purposes (80%) which are provided via the use of natural gas, fuel oil, and electricity. Electricity demand for appliances & processes as well as demand for heating and cooling purposes in buildings lead to an energy carrier mix in the tertiary sector, which is dominated by the use of electricity and natural gas. In industry, final energy demand is dominated by the use of natural gas, coal, oil, and electricity for energy-intensive production processes like steel, cement, or basic chemical production.

The European Commission's recently published long-term strategy (European Commission 2016) shows that emissions in the demand sectors must be drastically reduced in order to achieve the climate targets. However, as the sectors considered are very heterogeneous, so are the respective challenges for decarbonization. As the transport sector was not able to decrease GHG emissions within the last decades due to a strongly increasing transport activity, a combination of three main strategies seems required to meet the challenge of decarbonization: (i) increasing the efficiency of the transport system including a shift to lower emission transport modes, (ii) speeding up the deployment of low-emission alternative energy such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels, and (iii) accelerating the transition toward zero-emission vehicles.

The residential and tertiary sector face large challenges due to the high need of thermal renovation of the existing building stock as well as efficient new construction. Main challenges in the industry sector include the mitigation of process emissions from chemical reactions within the productions process, high-temperature needs and technical restrictions in industrial furnaces for the use of RES as well as feedstock demands for the chemical industry (currently mainly fossil-based).

In the following, the impacts of an ambitious mitigation scenario on future energy demand and CO_2 emissions for transport, industry, residential, and tertiary as well as its implications for demand-side flexibility are analyzed.

6.2 Scenario Assumptions and Model Coupling

The demand-side aspects of an ambitious mitigation scenario "well below 2 °C" correspond to an 80% emissions reduction of the entire system excluding carbon sinks and can be translated into sectoral carbon reduction targets for transport (61–63%), residential (87–91%), tertiary (88–93%), and industry (75–85%) (European Commission 2018). The considered mitigation scenario reflects a centralized energy system, which is characterized by external supply of RES secondary energy carriers and centralized district heating systems. The High-RES centralized scenario is analyzed in comparison to a reference scenario (Mod-RES) reflecting a current policy case based on known policies and observed trends (cf. Chapter 2). Important sector specific scenario assumptions can be summarized as shown in Table 6.1.

The results and analysis shown in the following sections have been carried out using three different types of models:

- the **long-term bottom-up simulation model FORECAST**: calculating annual future residential, tertiary and industrial energy demand and CO2 emissions on country level taking into account sector characteristics as well as a high level of technological detail (Fleiter et al. 2018; Herbst et al. 2017; Elsland 2017; Jakob et al. 2013);
- the **long-term system dynamics simulation model ASTRA**: calculating annual future transport energy demand and CO2 emissions on country level covering a wide range of transport measures and policies as well as alternative powertrain technologies for road vehicles (Schade et al. 2018; Fermi et al. 2014; Heitel et al. 2018);
- and **the hourly electricity load curve adjustment model eLOAD**: estimating the long-term evolution of the electricity system load curves on country level due to structural changes and new appliances as well as demand response activities (Klingler 2018; Gnann et al. 2018).

A detailed description of the used models and scenario assumptions can be found in Chapters 2 and 3.

6.3 Future Energy Demand and CO_2 Emissions

To achieve an ambitious mitigation level, major changes in the demand sectors have to take place in the medium and long-term. In addition to energy efficiency, another important pillar for a low-carbon demand-side transformation is fuel switch from fossil fuels (e.g., coal, natural gas, oil) to renewable energy sources (e.g., biomass, solar). However, energy efficiency and switching to renewables is likely not sufficient to achieve deep decarbonization especially for industry and transport (European Commission 2018). These sectors need additional strategies for significant emission

Table 6.1 Scenario characterization by sector

Mod-RES	High-RES centralized
Transport	
Targets and actions according to currently implemented European regulations	Policies to promote sustainable mobility, efficiency improvements, and multimodality More ambitious and extended CO_2 standards for new vehicles of all road modes Increased fuel tax for conventional fuels Further expansion of filling and charging infrastructure for electric mobility Sales ban of new pure internal combustion engine vehicles (urban buses: 2035, cars: 2040) Diffusion of fuel cell (FC) electric trucks based on R&D for FC technology, deployment of hydrogen (H2) infrastructure with centralized H2 production in large plants
Residential/Tertiary	
Building standards according to currently implemented national regulations Renovation rates remain on current level Implemented national incentives and subsidies for heating technologies stay in force Ecodesign directive in today's implementation & further announced reinforcement	Higher building standards, compliance, & financial incentives Increase in renovation rates Financial incentives for alternative heating systems Ban of oil boilers after 2030 in the residential sector Fuel tax on gas & oil Decrease in average lifetime of heating systems New efficiency classes & more products included in the Ecodesign directive after 2025
Industry	
EE progress according to current policies Fuel switch driven by energy & CO_2 prices	Faster diffusion of incremental process improvements. Innovative/radical process improvements Centralized hydrogen production off-site Financial support for RES technologies Increased recycling and material efficiency/substitution

reductions, as for example the use of secondary energy sources such as electricity and hydrogen.

A possible pathway for decarbonizing European demand is reflected in the High-RES centralized scenario (Fig. 6.1). In 2050 electricity becomes the dominant energy due to high electrification in all sectors (e.g., electrification of passenger transport by diffusion of battery electric and plug-in hybrid vehicles, the use of electric furnaces in industry, and high penetration of heat pumps in the tertiary and residential sector), this leads to an overall increase in electricity demand by 36% compared to 2015, from 2,732 to 3,706 TWh in 2050, which has to be provided from renewable energy sources. In addition to electricity, hydrogen as another secondary energy carrier based

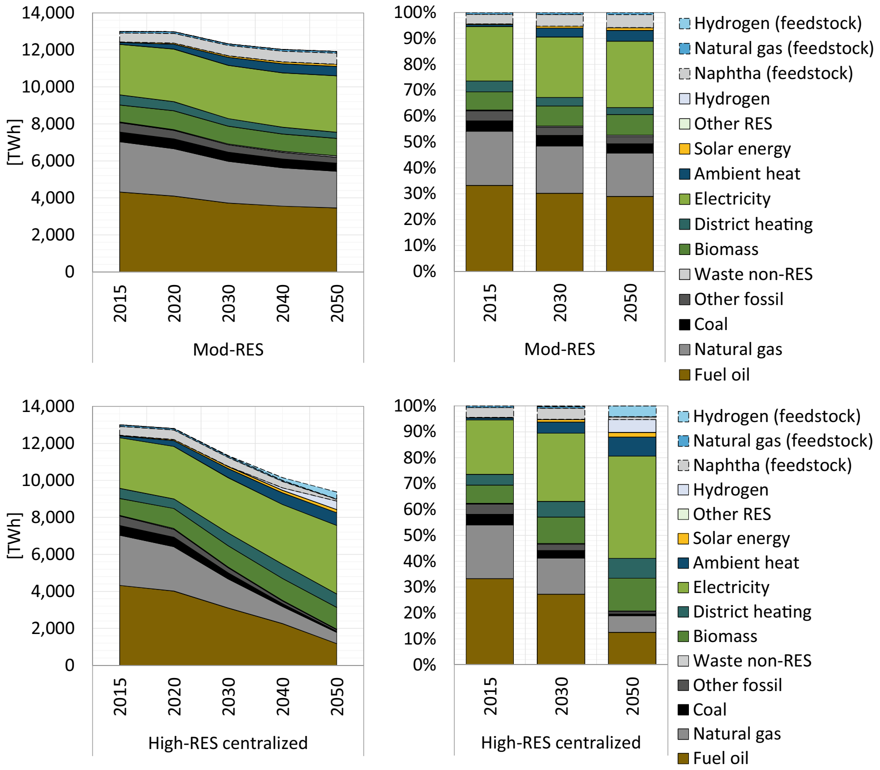

Fig. 6.1 EU-27 and UK final energy demand by energy carrier and scenario in TWh (2015–2050) (*Source* Own illustration)

on a CO_2-neutral production, e.g., via renewable energy sources, gains importance after 2030. Based on the model calculation, 845 TWh are needed in the transport in 2050 (418 TWh mainly for fuel cell electric trucks) and industry sector (427 TWh of which 384 TWh are used for feedstock production in the chemical industry). Biomass use is increasing by 269 TWh compared to 2015 caused by additional demand for biokerosene in aviation for the transport sector. Due to lower cost for centralized heat generation, the demand for district heating is increasing by 32% compared to 2015, from 549 to 723 TWh in 2050. The remaining demand for fossil fuels primarily stems from uses in the transport sector –1,205 TWh mainly from oil-based fuels—and the industry sector—470 TWh of which 299 TWh are natural gas. In the tertiary and residential sector 246 TWh of fossil fuels, mainly gas, are used in 2050.

This fuel switch is accompanied by high increases in energy efficiency in all sectors leading to an overall demand reduction of 28% compared to 2015, from 13,003 TWh to 9,376 TWh in 2050 (including the demand for feedstock in the chemical industry). Efficiency gains in the transport sector mainly stem from increased efficiency of vehicles, supported by modal shift of road transport demand to rail, public transport,

Table 6.2 EU-27 and UK direct CO_2 emissions by scenario and sector

Scenario/sector	2015	2050	Δ2015 (%)	Δ1990 (%)
Mod-RES	*2,218*	*1,818*	*−18*	*−29*
Transport	995	901	−9	+5
Residential	317	204	−36	−41
Tertiary	161	50	−69	−74
Industry	745	663	−11	−44
High-RES centralized	*2,218*	*585*	*−74*	*−77*
Transport	995	336	−66	−61
Residential	317	26	−92	−92
Tertiary	161	26	−84	−87
Industry	745	197	−74	−83

Source Own illustration

and other modes. In the residential and tertiary sector higher building standards, increased compliance and financial incentives for alternative heating lead to a strong increase in renovation rates and energy efficiency improvements (e.g., old direct electric heating, water boilers, and night storage heaters are being replaced by more efficient heat pumps). In addition, new efficiency classes and the inclusion of more products in the Ecodesign Directive lead to further reductions in demand after 2025. Also in industry, an ambitious exploitation of remaining energy efficiency potentials takes place (e.g., near-net-shape casting in the steel industry, new drying techniques in the paper industry, and efficiency improvements in electric motor systems). However, potentials for further improvement in this sector are limited due to already efficient production technologies. The introduction of innovative production technologies (e.g., low-carbon cement, RES H_2 direct reduced steel, RES H2 methanol, and ammonia) lead to significant reductions in industrial CO_2 emissions.

The high level of ambition in the High-RES decentralized scenario implies an overall direct emission reduction of 74% compared to 2015 (Table 6.2). Remaining emissions in 2050 mainly stem from oil demand in the transport sector (319 Mt) as well as industrial process emissions (80 Mt) and natural gas demand (60 Mt).

6.3.1 Decarbonizing the Transport Sector

The transport sector is currently responsible for about a third of final energy consumption in EU-27 countries and UK (European Commission 2017). Therein, fuel oil products are the dominant energy carrier, constituting around 93% of total energy demand for transport in 2015.

Transport and mobility demand are key to determine future energy consumption. ASTRA estimates an increase in transport demand until 2050, mainly caused by economic and population growth expected in the future decades. Passenger transport demand is expected to increase by 34% and freight transport by 60% in the period between 2015 and 2050.

In the Mod-RES scenario, in which only already implemented European regulations are considered, the EU-27 and UK total final energy demand is expected to decrease by modest 3% from 2015 to 2050, with fuel oil products still representing the main energy carrier (about 84%). The slight decrease in energy demand can be observed from 2020 on, due to the implementation of policies enhancing the efficiency standards for cars and vans (cf. Fig. 6.2).

In the High-RES centralized scenario, total energy demand is decreasing strongly, about 30% from 2015 to 2050, due to a modal shift from road transport to more efficient transport modes and substantial efficiency improvements in the vehicle fleet including new drive technologies. The composition of the energy carriers underwent a big change: the use of fuel oil represents about 40% of demand in 2050 while the remaining share is covered by electricity (22%), hydrogen (15%), and biofuels (18%).

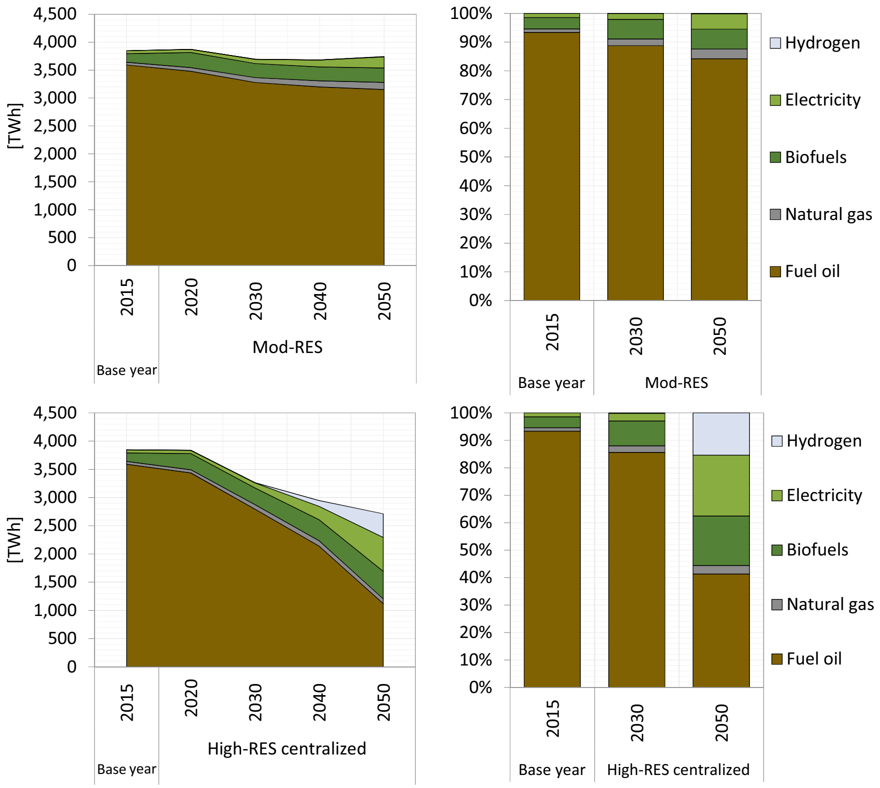

Fig. 6.2 EU-27 and UK final energy demand of the transport sector by energy carrier and scenario in TWh (2015–2050) (*Source* Own illustration)

The strong increase in electricity and hydrogen demand results from a technological change for road vehicles. The electrification of passenger transport by diffusion of battery electric (BEV) and plug-in hybrid (PHEV) vehicles leads to a total annual electricity demand of 600 TWh in 2050, thus being ten times higher compared to 2015. The hydrogen demand reaches about 420 TWh per year in 2050, driven by the market penetration of fuel cell electric trucks (80% of the hydrogen demand for transport) and spillover effects to the diffusion of fuel cell (FC) technology for cars, vans, and buses. The triplication of biofuel demand from 2015 to 2050 is triggered mainly by air transport. It is assumed that 43% of aviation fuel demand is covered by biokerosene in 2050 to reduce the high carbon footprint of the aviation sector, which is constantly growing in terms of transport activity, leading to about 220 TWh biokerosene demand.

6.3.1.1 Modal Shift

In general terms, rail transport, navigation, and public transport are more energy efficient compared to road transport (Faberi et al. 2015). Thus, shifts to these modes are preferable. Push and pull factors have to be combined, i.e., discouraging motorized road transport, e.g., by energy and vehicle taxation, parking space management, or road charging, and at the same time making non-road modes more attractive by investing in rail, cycling, and walking infrastructure, by improving public transport services and the availability of shared mobility, and by promoting multimodality with electronic information platforms and services that reduce waiting times, enable seamless electronic ticketing and real-time trip information.

Modal shifts for freight are difficult to obtain due to rare direct access to rail and waterways at origin and destination and thus required reloading operations. In the Mod-RES simulation, the modal share of road transport declines from 50% in 2015 by only 3% toward rail and ships to 47% in 2050. In High-RES, an unintended rebound effect was even induced in later decades: Policies pushing the diffusion of zero-emission technologies make road freight transport a clean and attractive alternative, so that road share regains to 49% in 2050. For passenger transport, a significant modal shift to public transport, car-sharing, and active modes like biking including e-bikes and walking was observed on the local level in the model.

6.3.1.2 Energy Efficiency of Vehicles

If motorized trips can neither be avoided nor shifted to more efficient transport modes, efficiency can be increased on the vehicle level. Efficiency improvements for road transport were achieved since 1990 with an average of −0.7% per year for cars and about −0.5% per year for trucks and light-duty vehicles (EEA 2019). The EU regulations on CO_2 emission performance standards for cars and vans provide an indication of the expected efficiency improvements until 2030 (Regulation (EU) 2019/631, 2011/510 and 2009/443): until 2021, a target reduction of about 27% with respect to 2015 is required in terms of fuel efficiency for new car vehicles, while for 2025 and 2030 the manufacturers will have to comply with a further reduction target of 15% and 37% for new cars. Approaches for high efficiency of vehicles are reduced resistance, e.g., via aerodynamic designs, lightweight materials and small vehicles, brake energy recuperation, and improved traffic flow through traffic management, harmonized speeds, driver training, as well as respective effects of connected and autonomous driving (e.g., Helms et al. 2010; Krail et al. 2019).

6.3.1.3 Diffusion of Low-/Zero-Emission Vehicles

Efficiency improvements of road vehicles contribute to the decarbonization process but are not enough to achieve the GHG emission reduction target. Therefore, a substantial change of energy carriers from fossil fuels to electricity and hydrogen is needed through the diffusion of alternative drive technologies, in particular, battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles. Their diffusion can be accelerated through measures like investments in charging and hydrogen infrastructure, tax incentives, tighter fuel efficiency standards and sales bans of new vehicles with conventional internal combustion engines. Drivers of the diffusion and resulting impacts for the energy system will be described more comprehensively in the chapter about disruptive technologies (cf. Chapter 7).

6.3.1.4 Alternative Fuels

Electricity-based synthetic fuels and biofuels are considered as a valuable decarbonization option for aviation and navigation that both lack mature alternative technologies and have long operation lifetimes of their crafts. Considering the relatively low efficiency of these alternative fuels from well-to-wheel as well as sustainability concerns of biofuels, increased use for road modes seems only reasonable in a transition phase. Biokerosene was approved for commercial use in 2011 and some airlines are experimenting with their use. Several studies confirm that the biokerosene blend can reduce air pollutant and GHG emissions (European Commission 2011). However, with current technologies, the target of halving the CO_2 emissions by 2050 with respect to 2005 cannot be met (IATA 2015). Therefore, more advanced, sustainable biofuels of the second generation (i.e., not in competition with food crops for human consumption) and third-generation (based on algae) or electrolysis-based power-to-x fuels need to be further developed, tested and production capacities to be built up.

6.3.1.5 Impact on CO_2 Emissions

Although the strategies modal shift, efficiency improvement of vehicles, diffusion of low- and zero-emission vehicles and alternative fuels are pursued in the business-as-usual scenario Mod-RES to a certain extent, their degree of implementation is far too low to meet the decarbonization target for the transport sector of -60% GHG emissions by 2050 compared to 1990 levels. The simulation of Mod-RES with ASTRA showed that only a small reduction of GHG emissions is achieved from 2015 levels (−9%), with even a net increase from 1990 levels (−7%), triggered by the consistently growing transport activity.

Therefore, a comprehensive set of policies and infrastructure deployment decisions acting on both technology diffusion and demand management are required to meet the target. Several combinations and forms of the presented strategies could be envisaged. With the measures assumed in the High-RES centralized scenario a decrease of transport CO_2 emissions by -61% was achieved, thus meeting the decarbonization target. The gap in model results for Mod-RES 2050 was closed in High-RES by policies that accelerate the diffusion of low- and zero-emission vehicles (further −30% CO_2 emissions compared to Mod-RES 2050), policies increasing efficiency improvements (−16%), biofuels (−14%), and modal shift (−14%). A sales ban of pure internal combustion engine cars in 2040 and a strong promotion of fuel cell electric trucks accelerate the technology change for road vehicles. Biofuels contribute in particular for decarbonization of aviation and navigation. Policies aiming at a modal shift to active modes, public transport, and sharing mobility take effect in particular on the local level. Thus, taking also efficiency improvements of vehicles into account, the largest tank-to-wheel CO_2 reduction in 2050 compared to 2015 is obtained for road modes, with approximately −90% for vans, −80% for cars and buses, and −65% for trucks. Air passenger transport emissions are reduced by about −30% in the same period by efficiency improvements and the use of biofuels.

6.3.2 Decarbonizing the Residential and Tertiary Sector

Today the residential and the tertiary sector are responsible for about half of the European final energy demand. The most important end-use in both sectors is the provision of space heating in buildings, which is currently dominated by the use fossil fuels such as natural gas and oil. The high share of electricity demand in the residential and tertiary sector mainly stems from the use of electric appliances and lighting as well as the demand for ventilation and cooling. However, electricity is also needed for domestic hot water generation (besides also gas and oil) and to a limited extent for the provision of space heating, e.g., via electric boilers.

To achieve ambitious CO_2 mitigation levels, both sectors need to make substantial further efforts to increase building efficiency and switch to alternative heating technologies. A possible pathway for decarbonizing EU-27 and UK residential and tertiary final energy demand is shown in the High-RES centralized scenario (cf. Fig. 6.3).

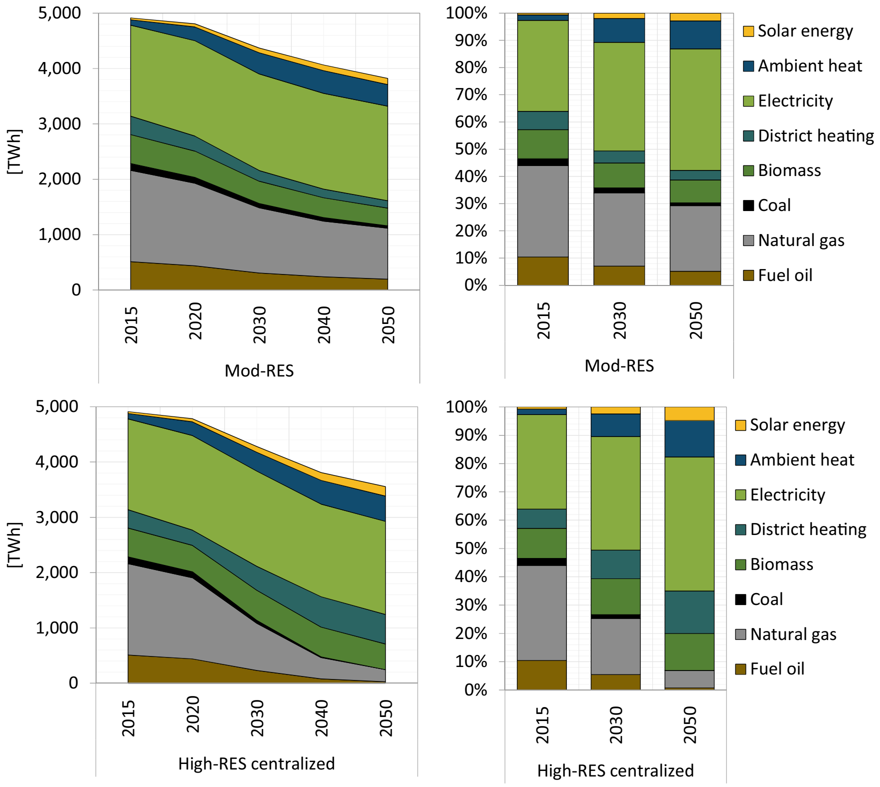

Fig. 6.3 EU-27 and UK residential and tertiary final energy demand by energy carrier and scenario in TWh (2015–2050) (*Source* Own illustration)

6.3.2.1 Energy Efficiency

In the tertiary and residential sector large efficiency gains already take place in the current policy Mod-RES scenario leading to a decrease in final energy demand in 2050 by 22% compared to 2015, from 4,913 TWh to 3,821 TWh. These improvements are mainly caused by the national implementations of existing building codes (e.g., EPBD Directive 2010/31/EU) and efficiency standards (e.g., Ecodesign Directive 2009/125/EC). The requirements of these building codes and directives are already very high but it remains partially open how strict their implementation will be. Given the cost curves for different refurbishment measures (Reiter et al. 2019), the implementation of dedicated refurbishment strategies is essential to achieve the required refurbishment rates indicated by the achieved results. Especially in the tertiary sector where building functions can often refer to multiple building code classes, this poses a challenge for the appropriate selection and application of the respective standards.

A higher adoption of efficiency classes for more products in combination with the introduction of new efficiency classes after 2025 lead, together with a deeper refurbishment depth complying to minimum standards, and the shorter lifetime of heating systems, to a further reduction in final energy demand by additional 6% compared to the Mod-RES scenario (−28% compared to 2015, from 4,913 TWh to 3,555 TWh).

The development of electricity demand until 2050 is strongly dependent on the efficiency increase and ownership rates of appliances, as well as the efficiency increase of buildings and the technology mix of heating technologies in the scenario. In the residential sector old direct electric heaters, water boilers, and night storage heaters are replaced by more efficient heat pumps leading to an increase in final electricity demand in both scenarios (18% in Mod-RES from 1,643 TWh to 1,708 TWh, 24% in High-RES to 1,684 TWh) having a slightly stronger penetration of heat pumps in the High-RES scenarios.

Appliances in the residential and tertiary sector are the main contributor of electricity demand in 2050. White goods like refrigerators, freezers, dishwashers, and washing machines as well as ICT appliances like laptops and TVs are regulated within the European Ecodesign Directive that sets mandatory requirements for energy-related products. Labeling and classification into efficiency classes and minimum standards of the products leads to a strong increase of the efficiency. Contrasting to the Mod-RES scenario, where the efficiency increase stems from stock turnover replacement of old products with more efficient ones complying with the current efficiency classes, the High-RES scenario includes more efficient products after 2025. Especially for dryers and refrigerators, a further efficiency increase can be observed until 2050, while for ICT appliances like laptops and TVs, the electricity consumption stays almost constant or increases, respectively, in both scenarios. The reason for this is the increase of the size of appliances and performance progress. In the tertiary sector, especially cooling demand is expected to increase due to more surface area cooled, therefore, limiting the efficiency gains due to more advanced appliances.

6.3.2.2 Fuel Switch

Although the absolute difference of final energy demand in the two scenarios is not very large, the energy carrier composition in the two scenarios is quite different. In the High-RES centralized scenario, additional support for district heating is implemented given the assumption that more district heating networks are reinforced and more buildings can be connected to it at lower costs than today. Thus, the district heating demand in the tertiary and residential sector increases by 61% compared to 2015 (from 332 to 534 TWh). In addition, incentives and installation subsidies for RES heating supply as well as the shorter lifetime of heating systems increase the demand for low-exergy sources like solar thermal by fourfold (from 34 to 170 TWh) until 2050. Due to competition with other sectors (e.g., transport and agriculture), the use of biomass is limited in the High-RES centralized scenario decreasing by 11% compared to today. The ban of oil boilers after 2030 in the residential sector, in combination with a fuel tax on gas and oil, leads to a significant reduction in fossil fuel demand for space heating. While coal is completely phase out until 2050 the demand for fuel oil (−95% compared to 2015) and natural gas (−87% compared to 2015) decreases significantly.

6.3.2.3 Impact on CO_2 Emissions

Overall emission reductions in both sectors are 89% compared to 2050 in the High-RES centralized scenario (84% in tertiary and 92% in residential). Especially in buildings, space heating demand is a main contributor to GHG emissions. To reduce these emissions, combined efforts in refurbishment rates, depths, and technology changes are needed. Furthermore, refurbishment is a prerequisite for the deployment of RES and electricity-based heating technologies, which are the main contributors to emission reduction in those sectors. However, reaching the EU targets includes major efforts from all actors and stakeholders as well as additional regulatory framework, especially to increase the refurbishment rate beyond the current levels. EU-wide regulations for building standards in the buildings sector are already in force and a main driver to reduce heating and consequently CO_2 emissions in the long-run until 2050. To allow for a more centralized provision of renewable heat, financial incentives as well as connection regulations and strategies are needed to tap the full potential. Heat pumps can play a certain role for decarbonizing heat demand in the tertiary and residential sector, but specific support measures such as geothermal potential zones need to be managed as well as further cost reductions achieved for tapping ground sources for ambient heat gains.

6.3.3 Decarbonizing the Industry Sector

The industrial sector currently accounts for about a quarter of the EU-27 and UK final energy demand, mainly using fossil fuels such as gas, coal, and oil, but also electricity. Energy-intensive processes and products like, e.g., steel (iron and steel), cement (non-metallic minerals), ethylene (chemicals), and ammonia (chemicals) dominate demand and CO_2 emissions in this sector. Even though, some sectors already use a high proportion of electricity and biomass (e.g., paper industry), industry needs to make significant further efforts to reduce the use of fossil fuels in the coming decades. A particular challenge is the reduction of process emissions, as these emissions can only be reduced by radical changes in the production process, product mix or the use of CO_2 capture and storage. In terms of end-use, most industrial greenhouse gas emissions result from high-temperature process heat, either in the form of steam or hot water, or from direct firing of different types of furnaces. The high temperatures and the specific technological requirements limit the use of renewable energies to biomass or secondary energy (Fleiter et al. 2019; Herbst et al. 2018a, b). A possible pathway for decarbonizing EU-27 and UK industry is shown in the High-RES centralized scenario (Fig. 6.4).

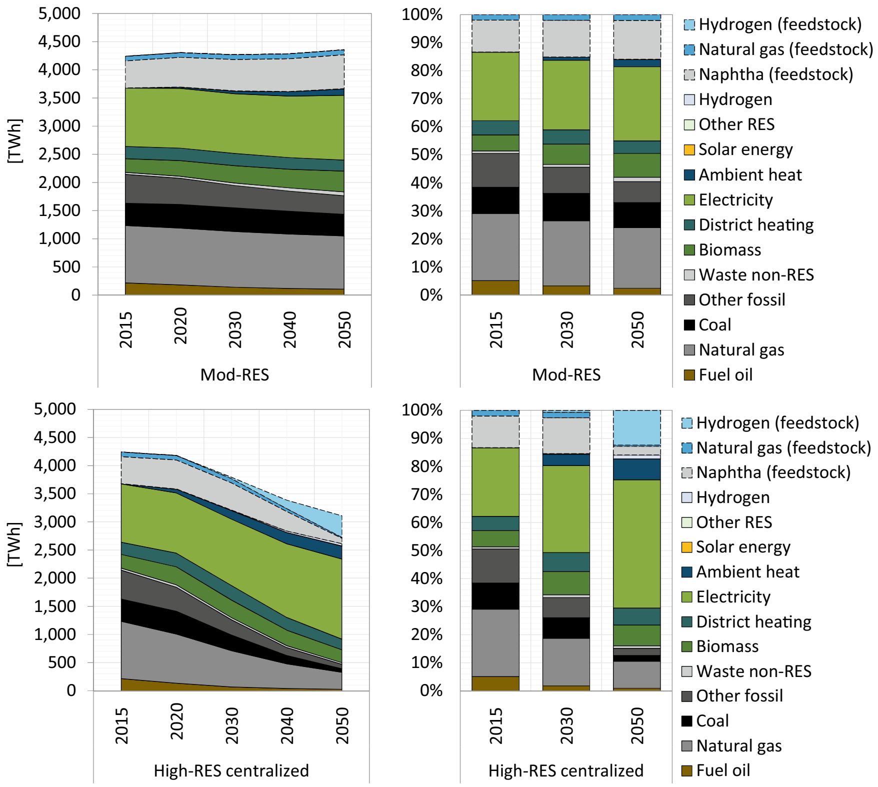

Fig. 6.4 EU-27 and UK industrial final energy demand by energy carrier and scenario in TWh (2015–2050) (*Source* Own illustration)

6.3.3.1 Energy Efficiency

The energy efficiency of technologies used today for the production of basic materials products like steel, cement, glass, or paper have been improved continuously over the past decades. The High-RES centralized scenario assumes a very ambitious exploitation of available energy efficiency potentials in combination with increases in material efficiency, material substitution and the recycling of materials—leading to a decrease in energy demand (incl. chemical feedstocks) in 2050 by 27% compared to 2015, from 4,243 TWh to 3,109 TWh. Still, the improvements realized in most processes are below 20%, indicating a limited potential for further process optimization in this sector (Herbst et al. 2018b). Exceptions are steel rolling, where new production technologies like near net shape casting or the paper production, where innovative new drying technologies can make a larger difference and materialize higher efficiency potentials. In addition to the energy-intensive basic materials processes, also cross-cutting technologies like electric motors and lighting account for a high share of total electricity demand, due to their widespread use. These systems are yet less optimized and remaining potentials are higher. Implementing remaining energy efficiency potentials by also optimizing the entire motor systems can further reduce demand until 2050 (Herbst et al. 2018b).

6.3.3.2 Fuel Switch

In the High-RES centralized scenario a comprehensive shift toward electricity as the dominant energy carrier in all sectors takes place in the model. This leads to an in increase in electricity demand by 37% compared to 2015, from 1,036 TWh to 1,422 TWh. Especially after 2030, the relevance of electricity as energy carrier increases significantly (46% in 2050 of total demand), due to an economic and regulatory framework which is in favor of electricity and the market entry of innovative electricity-based production technologies.

Switching to low-carbon fuels for the generation of process heat can be a major mitigation option, given that process heat today is mainly supplied by fossil fuels. Steam and hot water generation is used across all industries and covers a temperature range of up to 500 °C, which allows the use of combined heat and power (CHP) technologies. Another important field for fuel switching are industrial furnaces, which are very diverse and often work at high temperatures above 1000 °C, e.g., in the cement, glass, and steel production. Fuel switching is possible, but the use of energy carriers experiences higher technical restrictions and RES are sometimes difficult to integrate. In the High-RES centralized scenario it is assumed that in 2050 steel production from blast furnaces is substituted by direct reduction of iron based on RES electrolysis and RES H2-plasma steel production combined with an increasing share of electric arc furnace steel production. In the cement and glass industry production shifts to electric kilns and furnaces and in the paper industry and other steam using industries use high-temperature heat pumps well as electric steam boilers are used where applicable.

In addition, RES hydrogen is used in the chemical industry as feedstock for the production of methanol and ammonia (384 TWh in 2050) and consequently reduces CO_2 emissions for ethylene using methanol-based olefin production.

6.3.3.3 Impact on CO_2 Emissions

As best available technologies and conventional fuel switch are not sufficient to decarbonize the European industry sector until 2050, the strong emissions reduction in the High-RES centralized scenario reflects the high level of ambition implied in this scenario. Direct industrial emissions decrease by 74% compared to 2015, from 745 to 197 Mt in 2050. Remaining emissions in 2050 mainly stem from the use of natural gas (~30% of total direct emissions in 2050) and chemical reactions within the production process (process emissions: ~ 40% of total direct emissions in 2050). The main contributor of CO_2 emissions in 2050 is the non-metallic minerals sector (42% in 2050) including emissions from smaller point sources (e.g., bricks, lime, ceramics) and process emissions in the cement and glass industry. Further emissions remain in the chemical industry (16%) either from the use of natural gas or from process emissions in production. Sectors that are currently very CO_2-intensive today, such as the iron and steel industry or chemical feedstock production, become almost CO_2-free in 2050.

Important enablers are innovative efficiency technologies and the direct and indirect use of electricity in the scenario. Examples are direct reduction of iron based on RES electrolysis, electric kilns and furnaces and the use of RES H2 as feedstock for methanol/ethylene and ammonia production. Innovative products like low-carbon cement sorts (using new binders) can reduce the specific energy- and process-related cement emissions by between −30 and −70%. The scenario shows that decarbonization of the industrial sector is possible—even without carbon capture and storage—however, this requires process innovations, which currently strongly differ in maturity and distance to market, CO_2-free secondary energy carriers, and innovations in material efficiency and circular economy. Besides overcoming the barriers to market entry and setting up a regulatory framework, a main challenge lies in the fast diffusion until 2050. I.e., this scenario assumes that in most energy-intensive processes, the transition is completed in 2050, reflecting a very ambitious assumption.

6.4 The Future Need for Demand Side Flexibility

As explained before, efficiency improvements are likely to reduce electricity demand of end-uses. At the same time, the decarbonization of selected sectors (e.g., heating and transport) will be realized through a shift toward the use of carbon–neutral electricity, driving the diffusion of new electricity consumers. It is known that these changes in the electricity demand structure will not only affect the total amount of electricity that is consumed, but also change the shape of the system load curve[1] (Boßmann and Staffell 2015; Boßmann et al. 2015). This change in the hourly electricity demand in combination with increasing levels of fluctuating electricity generation from renewable energy sources (RES), is highly likely to result in increasing level of fluctuation in the residual load (i.e., the difference between the system load and electricity generation from RES). If electricity generation from RES exceeds the actual system load, the residual load drops below zero, meaning that RES need to be curtailed in the absence of alternative flexibility options. Thus, increasing shares of RES and a transforming system load curve could drive the need for conventional generation capacities, while the utilization, and hence profitability, of new and existing RES capacities could decline. Consequently, the challenge is to find appropriate measures that increase flexibility in the electricity system and smooth the residual load in order to balance supply and demand in a cost-efficient and sustainable manner (Boßmann 2015).

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[1] The system load curve is defined as the total hourly load of all electricity consumers in a country.

In this context, information is required about the electricity consumption behavior of the individual processes in order to properly represent the technological changes inside the system load curve. Depending on the type of process, electricity load profiles are available as either yearlong (i.e., 8,760 h) profiles, typical day profiles that vary between season (summer, winter, transition) and/or weekdays (Saturday, Sunday, weekday), or temperature-dependent profiles. The latter is particular relevant in case of heating and cooling processes. The applied load profiles in the eLOAD model stem from various public sources and from the internal database of the Fraunhofer Institute for Systems and Innovation Research ISI (for details, cf. Boßmann 2015). Temperature-dependent profiles are generally applicable for various countries, since they are adjusted using local weather data. However, if typical day load profiles are not available in a specific country, these types of profiles are transferred across countries via the information form time use surveys. Such surveys report the activity (such as working, sleeping, and food preparation) of a representative sample of individual persons based on time diaries (cf. Gershuny et al. 2014, Statistika Centralbyran 2014). In this study it is assumed, that for selected processes activities correlate with electricity consumption (e.g., the activity of working with the load profile for electric vehicle charging at work) and that countries, featuring the same activity pattern, can be characterized by similar load profiles.

The application of the described process-specific load profiles in the eLOAD model results in the projection of the system load curve into the future. Figure 6.5 summarizes the effects of individual load profiles and the net effect on the system load curve in the High-RES centralized scenario in 2050. In this scenario, hydrogen is produced off-site in central large-scale electrolyzers. Therefore, hydrogen is provided directly by the energy suppliers and not included in the sectoral electricity demand. In case of decentralized scenario world this would be different (cf. Chapter 7). Note that due to an easier readability, the individual industry processes are aggregated as well as the consumption in the individual demand-side subsectors regarding the lighting, cooling, and heating processes. The most important process clusters explaining structural changes in the future system load curve are labeled. Due to the increasing electrification, the electricity demand generally increases until 2050. In particular, in the midday and evening hours, the electricity demand increases due to the charging of electric passenger cars at home and at work. In the cold season, the electricity demand by heat pumps affect the future system load. The increasing electricity demand for heating purposes is compensated to some extend by decreasing demand for lighting purposes and the classical industry processes (such as lime milling, extrusion, etc.) due to efficiency gains. Overall the system load gains in fluctuation for all considered countries and increases in temperature sensitivity in most countries, due to an increase in demand of temperature dependent heating and cooling processes.

An example of the structural changes and increasing fluctuations in the system load is depicted in Fig. 6.6, which shows the average system load curve for typical days in the EU-27 + NO + CH + UK. Overall electricity demand increases by 36% between 2014 and 2050, while the peak load increases by 51%. The influence of electric vehicle charging, causing load peaks in the midday and evening hours particularly on weekdays, is clearly visible in 2050. The effect of heat pumps increasing the

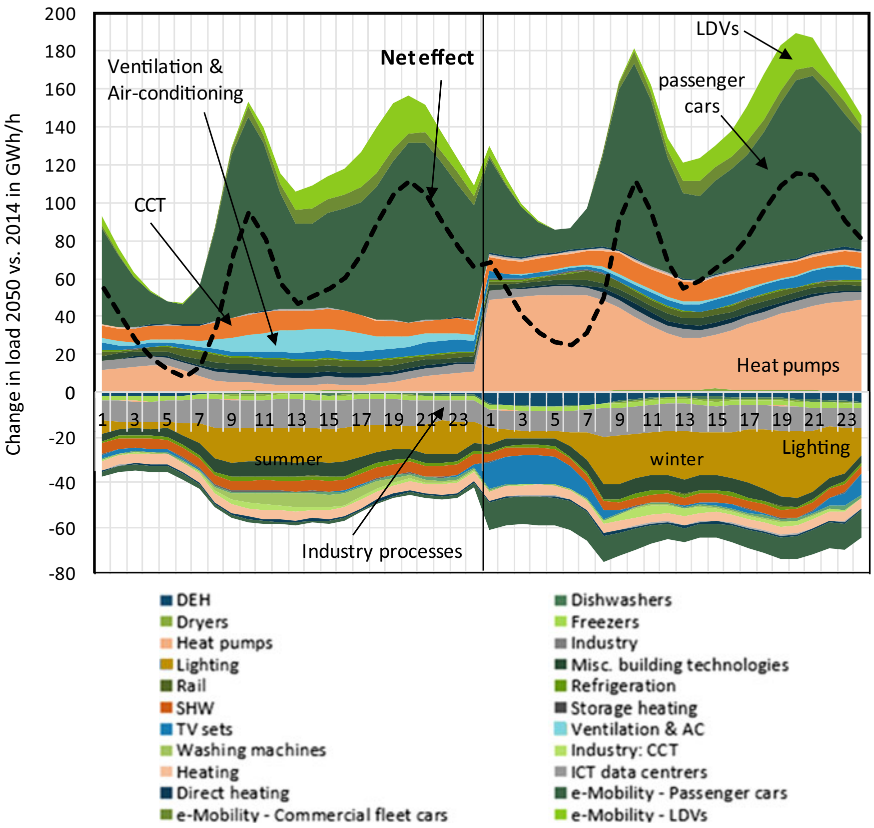

Fig. 6.5 Average load change 2050 vs. 2014 aggregation of the EU-27, Norway, Switzerland (The calculations for the hourly demand are done for these countries. Due to the lack of available data Malta is excluded from the hourly calculations), and the United Kingdom by process in summer (left) and winter (right)—High-RES centralized scenario (*Source* Own illustration)

average load on winter days is equally detectable, however, less pronounced due to the compensating effect of efficiency gains.

As explained earlier, increasing fluctuations drive the need for flexibility options. Furthermore, the fluctuation generation of electricity from RES leads to a highly fluctuating residual load curve that would have to be covered by conventional generation capacities if no flexibility options are available. Figure 6.7 illustrates the fluctuation in the residual load for the EU-27 + NO + CH + UK and shows the development of system load and residual load from 2020 (left part) to 2050 (right part).

Figure 6.8 shows the load changes of the EU-27 + NO + CH + UK's system load (left) and residual load (right) from one hour to the next as a load duration curve for the years 2014 to 2050. It is shown that the total electricity consumption changed by more than ±50 GWh/h from one hour to the next in 2050 in 382 h. In the years before, the maximum load change was +43 GWh/h (2014), +47 GWh/h (2030),

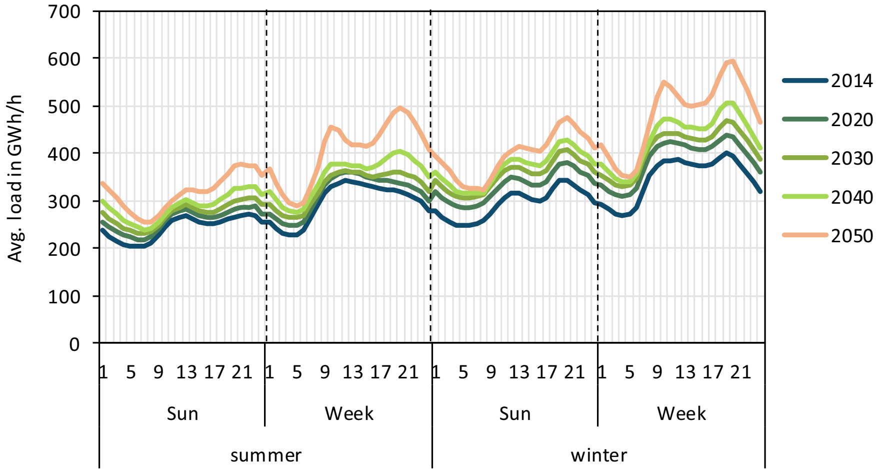

Fig. 6.6 Development of the average system load in the EU-27 + NO + CH + UK in summer and winter on Sundays and weekdays for the years 2014 to 2050—High-RES centralized scenario (*Source* Own illustration)

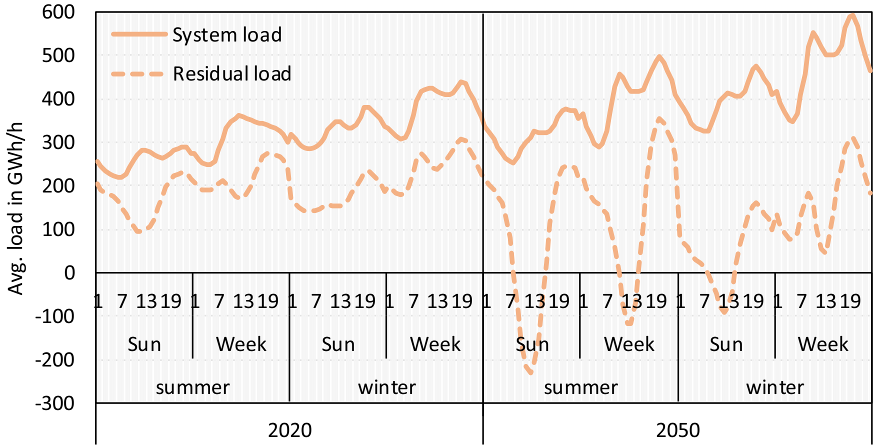

Fig. 6.7 Average system (solid line) and residual load (dashed line) of the EU-27 + NO + CH + UK in 2020 (left) and 2050 (right)—High-RES centralized scenario (*Source* Own illustration)

and +50 GWh/h (2040). The load changes in the residual load increase even more dramatically to 2,127 h with load changes of more than ±50 GWh/h (cf. Fig. 6.8).

Besides the effect of higher fluctuations in system and residual load curves, the system load curve increases in temperature sensitivity in the future in many EU countries. While energy efficiency decreases electricity demand on warm days due to more efficient ventilation and cooling systems, the increasing electrification of

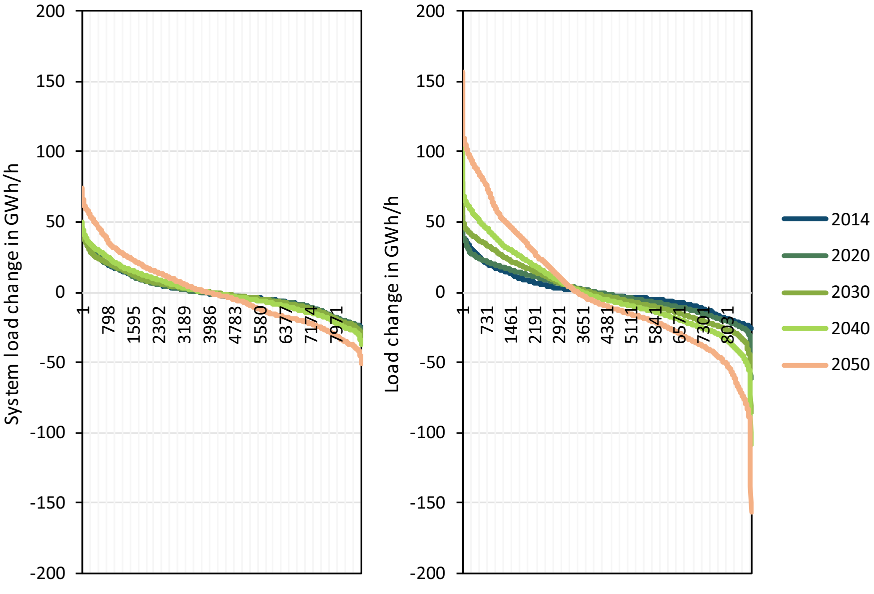

Fig. 6.8 Load duration curve for the EU28 + NO + CH's system load (left) and residual load (right) in the years 2014 to 2050—High-RES centralized scenario (*Source* Own illustration)

heating systems for space heating and hot water particularly in the residential and service sector leads to rising electricity consumption on cold days.

Overall the High-RES centralized scenario shows that changes in the residual and system load curve that are to be expected in a decarbonized RES energy system, which stresses the need for future demand-side flexibility. However, there is large uncertainty to which extent and at what point in time load management will be deployed throughout the EU countries. For a detailed analysis of demand-side flexibility in an ambitious mitigation scenario see Part III.

6.5 Conclusions

The analyses carried out in this study show that decarbonization of all demand sectors is possible until 2050. However, this requires massive efforts in all sectors and a policy framework supporting the necessary changes as well as CO_2-free secondary energy carriers. In a scenario without carbon capture and storage, renewable electricity becomes the most important energy carrier in all sectors in 2050 used either directly or indirectly, e.g., as renewable hydrogen.

In the transport sector, energy demand will change significantly if GHG emission targets are met by 2050. While electrification is a key solution for road transport, blends of biofuels or synthetic fuels will play a major role in aviation and navigation.

A combination of several strong measures and policies is required to meet the big challenge of decarbonizing a consistently growing transport demand. The diffusion of low and zero-emission drive technologies and further efficiency improvements of vehicles can contribute substantially. A large shift to the more efficient non-road modes would be even more preferable but requires a change of habits and handling processes, which is harder to achieve and predict.

In the residential and tertiary sector, refurbishment is a prerequisite for the deployment of RES and electricity-based heating technologies. Major efforts among all stakeholders are needed to increase energy efficiency in buildings and raise the refurbishment rate beyond current levels. Ambitious EU-wide regulations for building standards are already in force and the main driver to reduce heating and consequently CO_2 emissions in the long-run until 2050. Heat pumps can play an important role for decarbonizing heat demand in the tertiary and residential sector, but specific support measures such as geothermal potential zones need to be managed as well as further cost reductions achieved for tapping ground sources for ambient heat gains. A higher adoption of efficiency classes for more products in combination with the introduction of new efficiency classes will also be necessary to reduce electricity demand for appliances.

In industry, the analysis has shown that today's available technologies are not sufficient for deep decarbonization of the sector. Mitigation levels in industry of more than 80% can be achieved without the use of CCS, but needs the implementation of a variety of different mitigation options including energy efficient and low-carbon production innovations, renewable-based electricity, and hydrogen (also as feedstock for the chemical industry), a comprehensive circular economy and improvements in material efficiency. In order to achieve this, the current policy mix needs to be adjusted in order to effectively support R&D activities directed at the decarbonization of industrial production. In this context also public RD&I funding can play an important role. A European Emission Trading minimum price path will be needed to provide more long-term clarity and the certainty for investors. A CO_2 tax could provide fuel switching incentives for companies outside the ETS. Boosting material efficiency and a circular economy approach along the value chain also requires a broad policy mix (e.g., measures to increase recycling rate, measures to keep CO_2 price signals visible along the value chain) including targeted public procurement.

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Chapter 7
Disruptive Demand Side Technologies: Market Shares and Impact on Flexibility in a Decentralized World

Stephanie Heitel, Anna-Lena Klingler, Andrea Herbst, and Francesca Fermi

Abstract Electricity demand is expected to increase strongly as electrification and the use of hydrogen are promising decarbonization options for the demand side sectors transport and industry. In a decentralized system with volatile renewable energy sources, flexibility potentials will play an important role for secure and cost-efficient electricity supply. On the demand side, decentralized PV-battery systems and electric vehicles as well as hydrogen production by electrolyzers could provide the necessary flexibility. Energy demand over time is calculated based on assumed and simulated market shares of these and other low-emission technologies. Impacts on the system and residual load are analyzed, with a focus on the contribution of load shifting as a demand-side measure. Results indicate that load shifting can contribute significantly to integrate RES electricity.

7.1 Introduction

Decarbonization of the transport and the industry sector will most probably result in a much higher demand for electricity (cf. Chapter 6; European Commission 2018). To cope with the volatile electricity generation of renewable energy sources (RES) and consumption peaks, more flexibility on the supply and demand side is required for a secure and cost-efficient electricity supply (cf. Chapters 9–11).

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This paper focuses on analyzing flexibility potentials that can be provided by the demand side. Analyses are conducted for a decentralized energy system, meaning that hydrogen is produced locally in closer proximity to its consumers (cf. Chapter 2). In this scenario, we assume that consumers will support this decentralized system by installing rooftop PV systems and by engaging in demand side management (DSM) to provide flexibility to the system for a secure and cost-efficient electricity supply. Demand side management measures in this study aim to flatten the system load curves by reducing demand in peak times and at minimizing residual loads by adapting electricity consumption to electricity generation. The residual load is defined as the difference between system load curve and renewable electricity generation. By definition, a positive residual load means that the amount of electricity demand cannot be covered by RES. Negative residual loads occur when the production of renewable electricity exceeds the demand so that the renewable electricity cannot be integrated into the electricity system at this point in time (cf. Boßmann 2015; Chapter 6). In consequence, the reduction of negative residual loads by using demand side measures is an indicator that RES are used more efficiently. Furthermore, high fluctuations in the residual load curve can be a challenge for existing baseload power plants and could thus drive the need for additional conventional generation capacities, while the utilization, and hence profitability, of new and existing RES capacities could decline.

Compared to classical DSM measures such as heat pumps and refrigeration (cf. Chapters 8 and 12), batteries, as part of residential photovoltaic (PV) systems and in electric vehicles, as well as hydrogen electrolyzers can have a stronger role in providing flexibility in a decentralized energy system. As several decarbonization options exist for transport and industry that will have different impacts on the amount of electricity demand and the flexibility potential, the options of these sectors will be briefly described in the following.

7.1.1 Strategies for Decarbonizing Transport

For the decarbonization of the transport sector, several strategies are available and have to be combined to achieve the challenging greenhouse gas (GHG) reduction target: modal shift from road transport to more efficient transport modes like rail, inland waterways, public transport, and active modes, improvement of the vehicle efficiency, diffusion of low- and zero-emission technologies, and alternative fuels (cf. Chapter 6 for more details). Looking at the demand side flexibility of these options, only the vehicle technologies battery electric vehicles (BEV), plug-in hybrid vehicles (PHEV) and fuel cell electric vehicles (FCEV) can lead to demand side flexibility. BEV and PHEV constitute a promising technology in particular for cars and light duty vehicles. Although manufacturers are developing battery electric heavy duty trucks, hybrid trolley trucks and FCEV trucks appear to be more promising options for long-distances, as batteries for long distance trucks would be of large size and weight. It is not yet clear which of these technologies will prevail (cf. Plötz et al. 2018). Trolley trucks are more efficient from an overall energy perspective, however, they require a catenary system infrastructure on highways for which acceptance in the population might be an issue (cf. Wietschel et al. 2017). Concerning flexibility, trolley trucks need electricity while driving, whereas the production of hydrogen via electrolysis as fuel for FCEV offers load shifting potential.

7.1.2 Technologies for Decarbonizing Industry

For the decarbonization of the industry sector until 2050, a variety of different technologies and mitigation options are of importance. As available technologies and conventional fuel switch will not suffice to meet the climate targets on GHG reduction, the industry sector needs to open up remaining energy efficiency potentials in combination with high financial support for RES to promote fuel switching to biomass, power-to-heat, and power-to-gas.

In terms of end-use, most industrial GHG emissions result from high-temperature process heat, either in the form of steam or hot water or from direct firing of different types of furnaces. The high temperatures and the specific technological requirements limit the use of renewable energies to biomass or secondary energy sources. In this context, two types of electricity demand can be distinguished: the direct use of electricity for mechanical energy and heating, and the indirect use via electrolysis-based secondary energy carriers such as hydrogen (cf. Chan et al. 2019). These radical changes in industrial process technologies will be necessary to foster fuel switch to electricity and hydrogen in the iron and steel industry, the chemical industry, and the non-metallic minerals sector for electric smelting furnaces (e.g., glass industry).

To substitute coal-based primary steelmaking with steelmaking based on the direct reduction of iron ore with hydrogen, large amounts of renewable hydrogen (e.g., produced with electricity from renewable resources with Proton Electron Membrane (PEM) electrolysis) have to be available at competitive prices. Currently, a variety of different projects within the EU are working to have this technology ready for the market: the HYBRIT-project,[1] the SALCOS-project[2] and the H_2Future/SuSteel-project.[3]

Another option to reduce emissions from primary steelmaking is the direct electrolysis of iron ore (cf. Siderwin 2018). This option also requires high amounts of renewables electricity as alkaline electrolysis is used to produce direct reduced iron from iron ore using electrical energy to replace conventional blast furnaces (cf. Chan et al. 2019).

In the basic chemical industry, the use of renewable hydrogen as feedstock can substantially reduce GHG emissions in this sector (cf. Fleiter et al. 2019; Herbst et al. 2018). Conventional ammonia and methanol production based on fossil combustion

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[1] The implementing companies are SSAB, LKAB, and Vattenfall, cf. Vogl et al. (2018).

[2] The implementing companies are Salzgitter and Vattenfall, cf. https://salcos.salzgitter-ag.com/.

[3] The implementing companies are Voestalpine and VERBUND, cf. www.h2future-project.eu. https://www.k1-met.com/forschungsprogramm/susteel/, Chan et al. (2019).

are replaced, using hydrogen-based production routes: H_2 ammonia from electricity rather than through methane steam reformation and H_2 methanol based on water electrolysis with electricity, followed by hydrogenation of CO_2 as carbon source (cf. Chan et al. 2019; Dechema 2017).

Further emission reductions can be achieved by ethylene production via low-carbon Methanol-to-Olefins (MTO) leading to a strong increase in methanol demand (Chan et al. 2019; Dechema 2017).

Further, radical process changes take place in the cement production, assuming the market entry of low-carbon cement sorts. In addition, a stronger switch to secondary production takes place in this scenario in the steel, aluminum, glass, and paper industry, as well as increasing efforts for material efficiency improvements and substitution.

Looking at the future flexibility potential, the largest potential in the industrial sector stems from on-site hydrogen electrolysis (if electrolyzers are installed as assumed in the scenario of this study).

7.1.3 Focus of this Study: Disruptive Technologies with Demand Side Flexibility

This study focuses on the three technologies that are likely to be the bulk of demand side flexibility in the long-term: decentralized *batteries as part of residential PV systems and in electric vehicles*, as well as *electrolyzers* for the production of H_2 as fuel for freight transport and as feedstock and fuel for the industry sector. The target is to analyze their potential impact via load shifting on the residual load as an indicator for RES integration.

In the next Sect. 7.2, these three technologies will be described in more detail including their current status and factors influencing their diffusion. Section 7.3 describes the detailed scenario assumptions for a decentralized world (based on the decentralized High-RES scenario cf. Chapter 2), the model coupling approach and the methods used to calculate and simulate the diffusion of the respective technologies. In Sect. 7.4, the results are presented comprising the installed battery capacities as part of PV systems, technology diffusion in the vehicle fleet, radical process improvements in industry and the resulting demand for electricity and hydrogen. Section 7.5 analyses the impacts of these technologies on demand side flexibility. Finally, the results are discussed and conclusions including policy recommendations are drawn.

7.2 Disruptive Technologies with Flexibility Potential

7.2.1 Photovoltaic Systems and Stationary Batteries

In terms of the economic performance of residential PV systems, the rate of on-site consumed electricity (so-called self-consumption) is becoming ever more important due to increasing electricity prices and decreasing feed-in remuneration. Self-consumption is particularly profitable in markets with high electricity end-user prices and relatively low levelized costs of electricity for PV. Relatively low or no feed-in remuneration promote high self-consumption rates. In order to increase self-consumption, battery systems are available, which allow matching the electricity production of PV systems and the household's consumption (cf. Schill et al. 2017). Due to increasing production capacities and technological learning, prices for batteries are expected to decrease substantially (cf. Louwen et al. 2018; Schmidt et al. 2017; cf. Chapter 4). Lithium-ion batteries are currently the dominant technology (cf. Figgener et al. 2017).

Batteries for the enhancement of self-consumption are therefore widely discussed and are already selling in some local markets. In Germany, with its high end-consumer electricity prices, about every second rooftop PV system is already combined with a battery: In 2016, 45% of new PV installations under 30 kW in Germany included a battery (cf. Figgener et al. 2017). Moreover, Barbour and González (2018) find that 'PV + battery systems' are to become a better investment than 'PV only systems'. The expectation of a broad diffusion of stationary batteries sparks the hope that this technology will provide necessary flexibility for the future electricity system. Recent studies find that participating in the balancing power markets could potentially increase economic benefits for the battery owner (cf. Stahl et al. 2018; Sterner et al. 2015). Due to complicated legislation, this option is still at its very early stages but is seen as viable to fill the need for more flexibility in the system.

7.2.2 Battery Electric Vehicles

Global electric car sales and market shares are rapidly growing (cf. Chapter 5). In 2018, the new registrations nearly doubled the registrations of the previous year. The global electric car fleet achieved over 5.1 million vehicles (cf. International Energy Agency 2019). These numbers comprise BEV, in which batteries are the only energy source, and PHEV, which still incorporate an internal combustion engine (ICE) and contain smaller batteries. Looking at the market shares of new electric cars, Norway is the global leader with 46%, followed by Iceland with 17% and Sweden with 8% (cf. International Energy Agency 2019). These numbers show that electric vehicles (EVs) are a real technological option to decarbonize road transport and reduce air pollutants. Declining battery prices due to global learning effects in production (cf. Chapter 5; Heitel et al. 2019; Schmidt et al. 2017) are an important driver for the diffusion. EVs may soon achieve cost-parity with conventional vehicles based on the total cost of ownership (TCO). Further drivers will be technological improvements, like raising durability and energy density that enables longer ranges, as well as policies that incentivize automobile manufacturers to build up an EV portfolio. A high EV uptake will increase electricity demand and can challenge the power system in case of uncoordinated charging in times of peak demand, causing local overloading of distribution networks and the need for additional electricity generation. In contrast, however, EVs can also contribute to flexibility with DSM. The provided flexibility potential depends on several factors, in particular, the available charging infrastructure and charging patterns (cf. Gnann et al. 2018), and the willingness to participate in load shifting so that the timing of charging can be postponed to low-demand periods.

Such a controlled charging mechanism provides a respective flexibility potential that could even be enhanced through bidirectional charging, which would transform EVs into a distributed electricity storage from which electricity can be fed back to the grid or home (cf. International Energy Agency 2019). Besides regulation, willingness to allow load shifting will depend on price incentives that should compensate for disadvantages like reduced spontaneity for taking the car or a faster degradation of the battery due to more frequent and rapid charging cycles.

7.2.3 Hydrogen Electrolysis

The electrolysis of water into hydrogen and oxygen has the potential to become a key element in coupling the electricity, transport and industry sectors by providing fossil-free fuels and feedstock in a future sustainable world. Additionally, electrolyzers can provide flexibility to the electricity system: According to Buttler and Spliethoff (2018), the technological development of the last few years shows that electrolysis is on its way to large-scale flexible energy-storage applications.

Large-scale electrolysis systems, which are in the focus of this study, consist of several electrolyzers in parallel. Therefore, it is possible to vary the power consumption of the overall system over a wide range by switching off individual electrolyzers. In this manner, current state of the art systems allow for a load flexibility of 0–100% of the nominal load (this applies for PEM electrolysis, cf. Buttler and Spliethoff 2018). Additionally, 20% overcharging is possible without significant effects on the lifetime (alkaline electrolysis, cf. Gutiérrez-Martín et al. 2015).

Since the large-scale operation of electrolyzers for the decarbonization of the energy system is still an emerging market, the mode of operation, whether decentralized (local electrolyzers) or centralized (with infrastructure carrying H_2) is uncertain and both can be assumed (cf. De Vita et al. 2018). On the demand side, the future requirement of H_2 in the transport and industry sector is expected to drive the market uptake of this technology.

7.3 Scenario Assumptions and Methodology

7.3.1 Scenario Assumptions for High-RES Decentralized

For the High-RES decentralized scenario, several strong measures are assumed to accelerate the decarbonization in order to achieve the GHG reduction targets and specific characteristics of a decentralized energy system are considered.

To support decentralized PV electricity generation, it is assumed that all European countries allow feeding PV electricity into the public grid. The electricity can be sold to the current market prices, while feed-in tariffs and premiums are abolished. Self-consumed PV electricity is not burdened with any surcharges, taxes, or levies.

Policies and assumptions that accelerate the diffusion of BEV and PHEV comprise a strong expansion of charging stations, increased taxes for conventional fuels and for the registration of ICE vehicles, and a sales ban for new ICE cars as of 2040. In this scenario, fuel cells are pushed as the future technology for trucks by R&D expenditures, deployment of a hydrogen filling station infrastructure for trucks, and a decision against the installation of catenary systems for hybrid trolley trucks. In the decentralized world, hydrogen is produced on-site at the filling stations. As households with rooftop PV have a higher probability to buy an electric car (as indicated by some studies, cf., e.g., Scherrer et al. 2019) due to financial advantages by consumption of self-produced electricity and higher technical familiarity, the EV sales are further supported by strongly increasing PV installations. Besides, it is assumed that multi-modal transport is more accepted in a decentralized world which leads to increasing demand for car sharing vehicles that are predestinated for higher electric shares in their fleet (cf. International Energy Agency 2019).

Due to radical process improvements, a strong shift toward electricity and hydrogen takes place in the iron and steel industry (DR electrolysis, H_2 plasma, DR H_2 + EAF) and the glass industry (electric melting). Furthermore, the production of ammonia, methanol and consequently ethylene is no longer based on fossil sources (e.g., natural gas, naphtha) leading to a significant drop in demand for refinery products but increasing the need for RES hydrogen. Hydrogen is produced on-site for industrial purposes and consequently leading to a high on-site industrial electricity demand for hydrogen electrolysis.

Table 7.1 summarizes the main assumptions for the High-RES decentralized scenario that are characteristic for a decentralized energy system.

Furthermore, we assume that DSM measures will be stipulated in the near future to facilitate renewable integration on a local level. Therefore, ambitious shares of flexible technologies (referred to as “smart share”) are assumed. New flexibility options, namely, *decentralized batteries* and *hydrogen electrolyzers*, are considered to be 100% DSM ready from the time of their installation. “Classic” flexible technologies, such as heat pumps, refrigeration, etc., gain the DSM option with their refurbishment. As hydrogen is produced on-site at the industrial plants and at the filling stations for transport, the electricity consumption and flexibility potential is

Table 7.1 Main scenario assumptions for the High-RES decentralized scenario

	Main assumptions for a decentralized energy system
PV & stationary batteries	Feed-in of PV electricity to the public grid is allowed in all European countries. The electricity can be sold to the current market prices. Feed-in tariffs and premiums are abolished There are no surcharges, taxes, or levies on self-consumed PV electricity
Transport	Strongly increasing number of households with rooftop PV accelerates the diffusion of electric vehicles Hydrogen for FCEV trucks is produced on-site at the filling stations Higher acceptance of multi-modal transport increases the use of car sharing vehicles that have a higher share of electric drives
Industry	Faster diffusion of incremental process improvements (Best Available Technologies and Innovations ≥ TRL 5) High financial support for RES technologies (biomass, power-to-heat, power-to-gas) Radical changes in industrial process technologies drive fuel switch to electricity and hydrogen (Innovations ≥ TRL 5). Hydrogen for industry is produced decentrally on industrial sites Stronger switch to secondary production (e.g., EAF steel) and increasing material efficiency and substitution

Table 7.2 Assumed participation in DSM (i.e., "Smart share") over time in percentage, based on the assumption of a stipulated participation

	2020 (%)	2030 (%)	2040 (%)	2050 (%)
Tertiary, industry sector	6	50	92	99
Residential sector	3	50	92	99
Hydrogen electrolysis	100	100	100	100
Stationary batteries	100	100	100	100
Electric vehicles	8	50	92	99

accounted for on the demand side. The smart shares for the tertiary, industry, and residential sectors as well as for batteries and electrolyzers are presented in Table 7.2.

7.3.2 Model Coupling Approach

For the simulation of the High-RES decentralized scenario across sectors, several models were coupled by data exchange in two iterations to include feedback mechanisms like the changing electricity price with the diffusion of additional demand side technologies (cf. Chapter 3 for more details on the single models and the data exchange). In the following, only the main models, linkages, and outputs that are required for the analysis of flexibility provided by the demand side are briefly explained. The two models—FORECAST, covering the industry, tertiary and residential sectors, and ASTRA, representing the transport sector—simulate the development of the annual electricity and hydrogen demand until 2050 by technology and consumer type, such as specific industrial processes or vehicle categories. In eLOAD, this annual demand is then translated to hourly demand curves by using load profiles of various technologies and consumer types. The resulting hourly system load curves are then optimized using demand side management with the assumed smart shares, to flatten the system load, and to reduce the negative residual load. For the calculation of the residual load, intermittent RES electricity from wind and PV are calculated by geographically highly resolved data on land availability as well as hourly time series of RES generation based on weather data, as described in Zöphel et al. (2019) and Slednev et al. (2018). Methods addressing the diffusion of the relevant technologies are described in the following section.

7.3.3 Methods Used for Technology Diffusion

7.3.3.1 Calculation of PV and Battery System Diffusion

The market diffusion of decentralized battery systems in households is calculated in five steps: first, the optimal (self-consumption maximizing) battery operation is calculated. In a subsequent step, the economic benefits of the battery system are assessed for batteries with different capacities, and the—on average—optimal battery capacity is selected with the assumption that feed-in premiums and tariffs are abolished, and the electricity produced by PV systems can be sold to the public grid at spot market rates. In the third step, Rogers' theory on the diffusion of innovation (cf. Rogers 2003) is applied to assess the share of battery adopters among PV system owners. Based on the share of adopters and the current and future population of PV system owners, the total population of battery adopters is calculated in a fourth step. In a final step, the installed battery capacity is given for the years 2016 to 2050. The calculations and assumptions are described in more detail in Klingler et al. (2019).

7.3.3.2 Diffusion of Alternative Drive Technologies for Vehicles

In ASTRA, the technology choice is implemented based on an adapted TCO approach that considers the following factors: vehicle prices, costs for energy consumption, maintenance costs, taxes, insurance, road charges as well as fuel procurement costs which depend on the deployment of the charging and filling station infrastructure and the ranges of the vehicles. The costs of the two new technology components i) battery and ii) fuel cell stack as part of the vehicle prices develop via experience curves covering global learning. Further qualitative aspects of purchase decisions related to a certain technology (like the anxiety of gas explosions or insufficient ranges, limited available vehicle models, etc.) are covered in a "residual disutility" term. The diffusion of technologies in the road vehicle fleet is simulated separately for the vehicle categories private cars, commercial cars, light duty vehicles, heavy duty vehicles in four separate gross vehicle weight categories, urban buses, and coaches. A set of suitable technologies is available for each category. The technology share for new vehicle purchases in each category is finally estimated with a discrete choice approach per country. The methodology is described in more detail in Heitel et al. (2019) and Krail (2009).

7.3.3.3 Assumptions for Technology Shares in Industry

The diffusion of new production processes is an exogenous assumption in FORECAST. Data on potential market entry and maximum diffusion rates were determined in previous projects by means of expert surveys and interviews (cf. Eichhammer et al. 2018) as well as literature analysis (cf. Chan et al. 2019). Therefore, the scenario can say little about the actual speed of process replacement and diffusion. It can, however, allow important conclusions on the overall direction of process change.

For the iron and steel industry, it has been assumed that oxygen steel will be replaced as far as possible with electric steel and that the remaining blast furnace route will be substituted with electrolysis-based direct reduction and hydrogen-based steel production routes (H_2 plasma steel, DR H_2 + EAF).

In the chemical industry, it is assumed that the production of ammonia, methanol, and consequently ethylene is no longer based on fossil sources (e.g., natural gas, naphtha) but fully substituted by renewable hydrogen and ammonia production as well as methanol-to-ethylene production in 2050.

7.4 Results: Diffusion of Technologies and Energy Demand

7.4.1 Installed Battery Capacity

In the mid- to long-term future, larger batteries are installed in residential PV self-consumption systems, due to decreasing technology costs. Based on technological learning, the specific investment decreases substantially, from 1,250 EUR/kWh in 2017 to 346 EUR/kWh in 2050 (cf. Klingler et al. 2019). Apart from the country of Norway, where the low electricity prices inhibit the batteries to gain an economic case, this cost development allows for high diffusion and large systems. In 2050, over 80 million batteries are expected in the EU-27 + CH + NO + UK, i.e., over 90% of the households with a PV rooftop system own a battery.

Table 7.3 shows the resulting on average installed battery capacity and Table 7.4 the total installed battery capacity for selected EU countries and the entire EU covering EU-27 + CH + NO + UK.

Table 7.3 Most economic battery capacity in kWh for the average household in selected countries in the years 2020, 2030, 2040, and 2050

Country	2015	2016	2017	2018	2019	2020	2030	2040	2050
DE	0	0	2.5	5	5	5	5	5	5
ES	0	0	5	5	5	7.5	7.5	7.5	7.5
FR	0	0	2.5	5	5	7.5	7.5	7.5	7.5
IT	0	0	2.5	2.5	5	5	5	5	5
NL	0	0	0	2.5	2.5	2.5	5	5	5
PL	0	0	0	0	2.5	2.5	2.5	2.5	5
UK	0	0	0	2.5	5	5	7.5	7.5	7.5

Source Data based on own calculations

Table 7.4 Expected installed battery capacity in MWh in Europe and in selected EU countries

Country	2020	2030	2040	2050
DE	2,404	39,003	54,865	63,861
ES	162	14,186	45,873	68,563
FR	1,264	36,108	73,182	100,286
IT	250	13,067	28,725	62,404
NL	0	2,000	6,392	5,329
PL	0	829	7,671	10,236
UK	0	6,053	36,033	45,942
EU-27 + CH + NO + UK	4,145	126,765	319,267	467,567

Source Data based on own calculations

7.4.2 *Vehicle Fleet Technology Composition and Resulting Energy Demand*

With the assumptions for the High-RES decentralized scenario, BEV, PHEV, and FCEV diffuse substantially in the car fleet, comprising over 80% of total passenger car stock of the EU-27 countries and the UK in 2050. Decreasing battery prices, stricter CO_2 standards for cars, extended charging infrastructure, diverse financial measures, and an increasing number of households with rooftop PV systems lead to a visible diffusion of BEV and PHEV in the upcoming decades. The diffusion accelerates from the year 2035 onwards as sales of new conventional ICE cars (i.e., gasoline, diesel, liquefied petroleum gas [LPG], and compressed natural gas [CNG]) are banned from 2040 onwards, having effects on car manufacturer's vehicle portfolios and purchase decisions already in the previous years.

For road freight transport, diesel remains the dominant fuel for the next two decades. BEV and PHEV prevail for trucks of the lightest weight category as prices for batteries decline, the number of available vehicle models increases and a growing number of cities restricts the entry of ICE vehicles. With more ambitious policies that increase costs for diesel trucks (i.e., stricter CO_2 standards, emission-based registration taxes, fuel taxes, and road tolls) and a reliable H_2-refueling infrastructure for heavy-duty vehicles, FCEV diffuse in the truck fleet as of 2030, achieving a share of 36% of all trucks in 2050. In order to enable market-entry based on a TCO approach, R&D and subsidies for fuel cell technology and hydrogen supply are required initially. Over time, the related cost further decline via experience curve effects for the production of fuel cell stacks and electrolyzers.

Figure 7.1 visualizes the diffusion of the low- and zero-emission technologies in the main road vehicle fleets in the High-RES decentralized scenario.

The resulting demand for electricity and hydrogen is depicted in Fig. 7.2. While the final electricity demand for the transport sector stems mainly from trains in 2015,

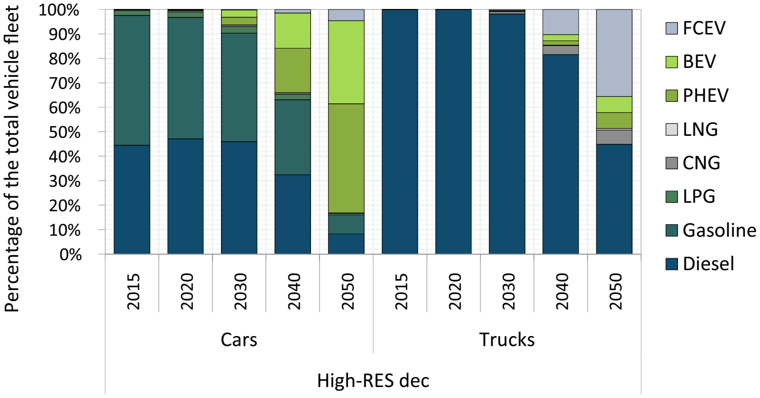

Fig. 7.1 Technology composition of the vehicle fleet in the High-RES decentralized scenario for cars and trucks for EU-27 + UK (*Source* Data based on model results from ASTRA)

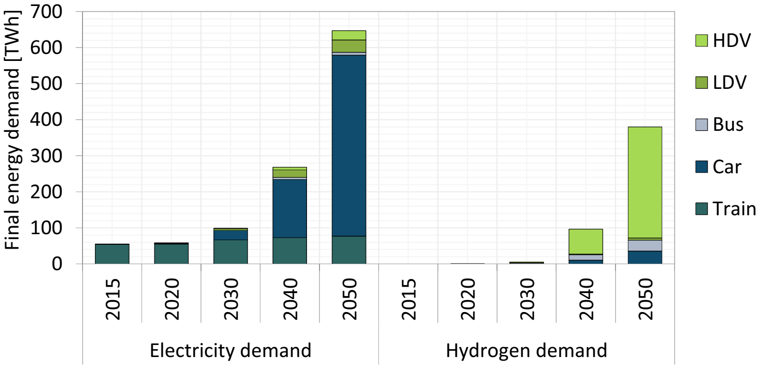

Fig. 7.2 Final electricity and hydrogen demand of the transport sector in High-RES decentralized for EU-27 + UK in TWh (*Source* Data based on model results from ASTRA)

the sector's electricity demand increases by ten times to 547 TWh in 2050 due to the diffusion of BEV and PHEV. Therein, electric passenger cars are the dominant consumers. They represent 88% of electricity demand from road transport and 14% with regard to total electricity demand.

The final hydrogen demand of the transport sector is strongly increasing from 2030 onwards with the diffusion of fuel cell trucks, reaching 380 TWh by 2050. Although hydrogen is also demanded by cars, light duty vehicles (LDV), and buses, 80% of the hydrogen required for the transport sector will be consumed by heavy duty vehicles (HDV).

7.4.3 Radical Process Improvements in Industry and Their Implications for Future Electricity Demand

In the High-RES decentralized scenario, a significant reduction of direct emissions in the industry sector is achieved (73% compared to 2015). This high level of ambition leads to a significant increase in demand for RES electricity and RES hydrogen in 2050, making electricity the dominant energy carrier in 2050 (from 1,036 TWh to 1,469 TWh in 2050, cf. Figure 7.3). Process technologies in 2050 use electricity either directly (e.g., DR electrolysis in the steel industry) or indirectly (e.g., production of ethylene via H_2-based methanol). Where possible, the direct use of electricity is preferred over the indirect use (e.g., electric kilns and furnaces). In general, electricity, ambient heat, and biomass substitute a large part of industry's demand for natural gas in this scenario.

In 2050, 42 TWh hydrogen use is assumed in the High-RES decentralized scenario within the iron and steel industry for direct reduction. H_2 feedstock use is assumed to take place at a large-scale leading to additional 384 TWh of hydrogen demand to the industrial final demand (cf. Figure 7.3 and Fig. 7.4). When produced on-site, this hydrogen demand together with the strong electrification of the industry sector lead to a doubling of industrial electricity demand in 2050 compared to 2015 (from 1,036 TWh to 2,078 TWh in 2050). Only the hydrogen demand for feedstock translates into approximately 549 TWh of additional electricity demand (cf. Figure 7.4).

7.5 Impacts of Disruptive Technologies on Demand Side Flexibility

With the ambitious electrification in the demand side sector, the electricity consumption in the High-RES decentralized scenario is much higher in 2050 compared to today's level. The high electricity demand in the study stems in particular from the assumption that hydrogen, for the transport sector as well as for feedstock and fuel in

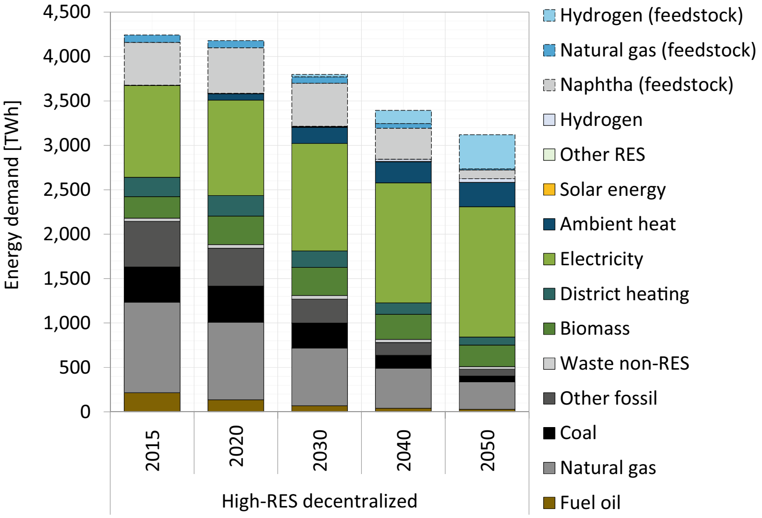

Fig. 7.3 Industrial final energy demand by energy carrier including feedstock demand for EU-27 + UK (2015–2050) (Dotted bars relate to feedstock demand. Hydrogen is split up into feedstock and energetic use. Electricity consumption does not include demand for hydrogen electrolysis. *Source* Data based on model results from FORECAST)

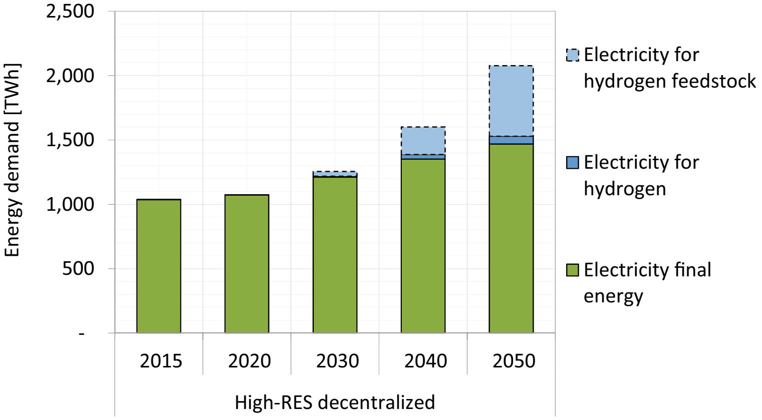

Fig. 7.4 Industrial final electricity demand including demand for hydrogen electrolysis for EU-27 + UK (2015–2050) (*Source* Data based on model results from FORECAST)

the industry sector, is produced via electrolysis decentralized at the filling stations and in industrial plants. Thus, the electricity consumption for electrolyzers is included in the system load and thus increases the national and EU-wide electricity demand. The electrolyzers feature a band-like profile with high full load hours, therefore the electricity demand increases in all hours of the year if no demand side management is applied.

Besides the hydrogen production, the future system load is expected to increase due to electricity consumption by battery electric vehicles. The charging of electric vehicles occurs in the High-RES scenario after the last trip at home, and additionally at the workplace. This particular charging pattern leads to load peaks in electricity consumption on midday and in the evening. Since electric vehicle charging makes up a substantial amount of the overall electricity consumption, the charging pattern shows in the system load curve (Fig. 7.5, left part).

Besides the analysis of structural changes in the system load curve, the changes in the residual load curve (i.e., the system load curve minus the renewable electricity production) are important to address. Figure 7.5 (right part) depicts the average residual load in summer and winter for the countries EU-27 + CH + NO + UK for the years 2020 and 2050. The increasing electricity consumption in the scenarios together with a higher amount of RES generation results in highly fluctuating residual loads and an increasing amount of negative residual load. A negative residual load indicates that an excess of renewable electricity is produced, i.e., the renewable electricity cannot be consumed within the system. The fluctuating or even negative residual load usually corresponds with equally highly fluctuating electricity prices, leaving room for DSM to exploit the arbitrage.

Figure 7.6 shows the shifted load due to DSM as the sum of load shifting in the countries EU-27 + CH + NO + UK in the High-RES decentralized scenario. Since we assumed high participation rates in this scenario, the results give an indication of the potential of DSM measures to smoothen the residual load and absorb price fluctuations. For better readability, the DSM processes in the figure are grouped: Ventilation and air-conditioning (V&AC) contains loads of the household and tertiary sector, the

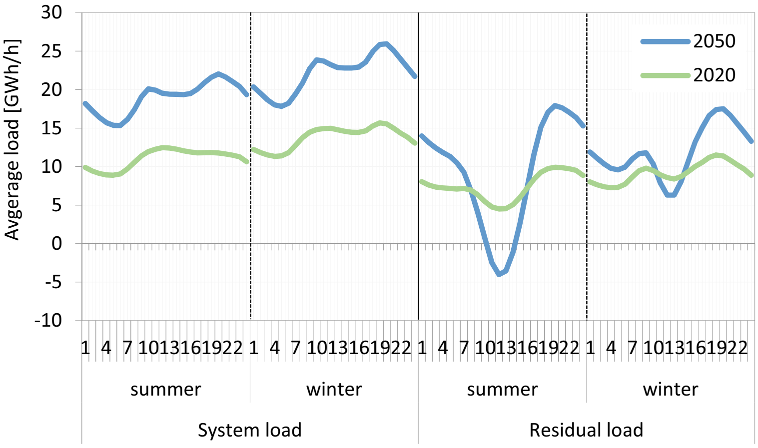

Fig. 7.5 Average system (left) and residual load (right) in summer and winter for EU-27 + CH + NO + UK in 2020 and 2050 (*Source* Data based on model results from eLOAD)

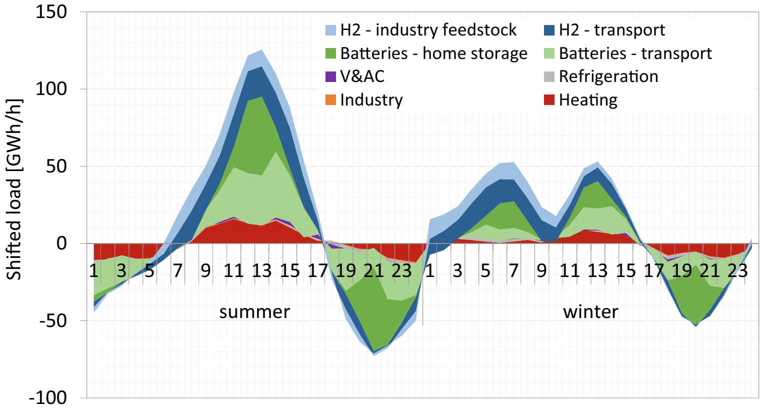

Fig. 7.6 Average shifted load in summer (left) and winter (right) for EU-27 + CH + NO + UK in 2050, distinguished by DSM process (*Source* Data based on model results from eLOAD)

same for electrical heating that is mainly heat pumps, but also contains direct electric heating and storage heating. "Industry" groups all industrial DSM processes, i.e., electric arc furnace, cement grinding, mechanical pulp. Equally, private and commercial battery electric vehicles are grouped (Batteries—transport).

Figure 7.6 shows that, in 2050 in the summer season, load is shifted mostly from night hours toward the middle of the day with high PV production and low or negative residual loads. In the winter season, the flexible loads are additionally shifted to the early morning hours with low electricity demand and therefore a relatively low residual load.

The resulting system and residual load curves of the load shifting is depicted for average summer and winter days in the years 2020 and 2050 in Fig. 7.7. The system load curve in the right part that represents the average electricity consumption of the EU-27 + CH + NO + UK shows that the electricity consumption increases in the midday hours due to the flexible deployment of decentralized hydrogen production, batteries and other, smaller flexible technologies. The residual load curves in the right part show a reduction of the hours with negative loads, i.e., on average, there is no excess electricity produced. Due to the high amount of flexibility in the future electricity consumption (e.g., in hydrogen production), the residual load shows an almost flat profile. For example in Germany, the residual load's standard deviation is reduced by 75% in 2050 compared to the residual load without load shifting.

Looking at the average summer and winter days depicted in Fig. 7.7, which reflects the sum of all EU-27 + CH + NO + UK countries, the issue of excess RES electricity production seems to be largely absorbed by higher and more flexible electricity consumption in the future. However, by the view on a country level, we find that for some countries there is still excess RES electricity produced. In particular in countries with high renewable potentials and relatively small (flexible) electricity consumption. Figure 7.8 illustrates the maximum available flexible load in the EU-

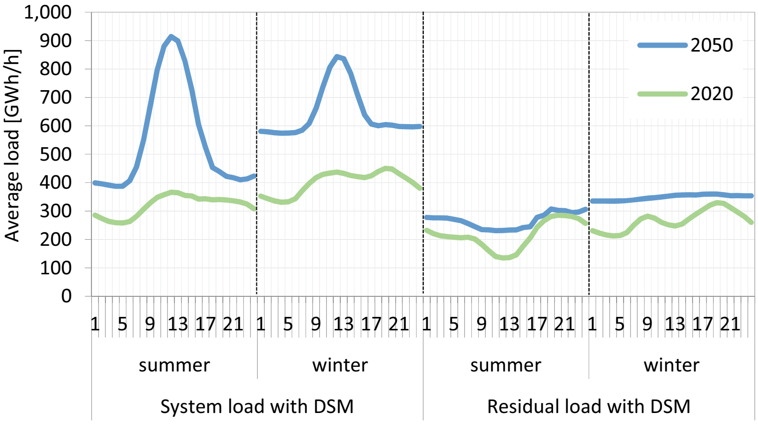

Fig. 7.7 Average system (left) and residual load (right) after DSM optimization in summer and winter for EU-27 + CH + NO + UK in 2020 and 2050 (*Source* Data based on model results from eLOAD)

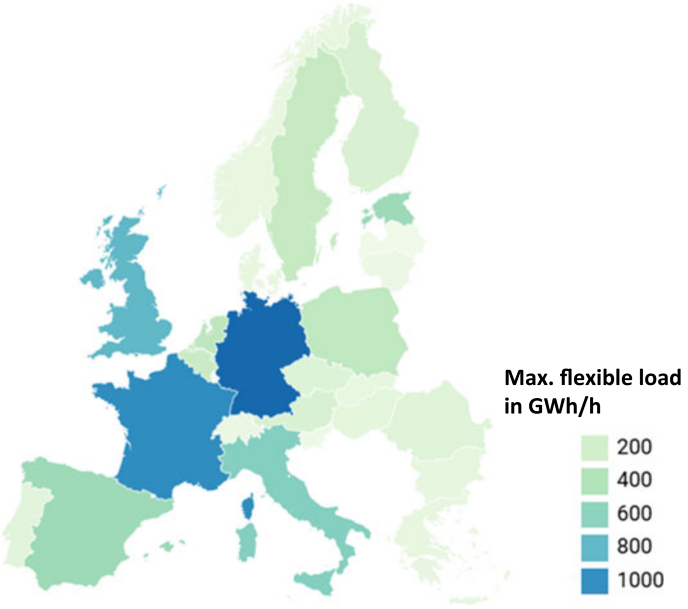

Fig. 7.8 Maximum shiftable load in the countries of the EU-27 + CH + NO + UK in 2050 (*Source* Data based on model results from eLOAD)

Table 7.5 Negative residual load vs. integrated RES for the largest EU countries and the entire EU-27 + CH + NO + UK in the High-RES decentralized scenario in TWh

	FR	DE	ES	IT	NL	PL	UK	$\sum$ EU−27 + CH/NO/UK
Neg. residual load without DSM	0.3	1.6	0.0	0.0	22.2	–	26.7	**55**
Reduction of negative residual load via DSM	0.3	1.5	0.0	0.0	9.5	–	14.8	**27**

27 + CH + NO + UK in the year 2050. The large European economies, e.g., Germany, France, and the UK, show the highest potential for flexible adjustments of their electricity demand. However, due to their high future electricity demand and limited RES production, they are not necessarily the countries with large excess electricity production.

Table 7.5 lists the amount of negative residual load in the largest European countries and the entire EU-27 + CH + NO + UK, and the reduction of negative residual load by means of load shifting as the most relevant DSM measure. The reduction of negative residual load is an indicator of RES electricity that was integrated into the electricity system due to DSM.

The Table 7.5 shows that countries, such as the UK and the Netherlands, with high flexible electricity demand and a high RES electricity feed-in, are able to apply their flexibility potential to integrate excess renewable electricity. Other countries, such as France and Spain, cannot fully use their flexibility potential for the integration of RES due to the limited renewable electricity generation.

7.6 Discussion and Conclusions

Market shares of the disruptive demand side technologies as shown in this chapter, especially focusing on the decentralized High-RES scenario, would enable to decarbonize the industry and the transport sector to an extent that their GHG reduction sector targets are achieved. However, to obtain this level of diffusion of innovative technologies and processes, strong measures and policies are required within the next decades to support market penetration.

For the diffusion of low- and zero-emission vehicles, financial incentives relative to conventional vehicles are required, implemented, e.g., by fuel taxes, registration fees, CO_2 prices, road charges, subsidies, or R&D expenditures. In addition, the infrastructure for charging, including fast chargers, and for fuels like hydrogen must be deployed in a reliable extent across countries to avoid range anxieties or extra efforts for fuel procurement activities. Spreading sales bans for ICE cars as of 2035/2040, which are already planned in several countries (cf. International Energy Agency 2019), across Europe would accelerate the decarbonization. Concerning low-emission trucks, decisions on the deployment of hydrogen refueling stations for FCEV versus catenary system infrastructure for trolley trucks must be taken after further experimentation and evaluation within pilot studies. This choice will have a noticeable impact on the provided flexibility potential. Moreover, the overall demand for electricity and hydrogen as well as the provided flexibility potential will depend a lot on the transition type for decarbonizing the transport sector. The High-RES scenario represents a mainly powertrain technology-driven decarbonization pathway. In case of more extensive lifestyle and behavior changes, e.g., with decreasing car-ownership rates, more use of multi-modal transport, micro-mobility, biking and walking, and large fleets with shared and autonomous cars, impacts on the electricity system might be quite different both in terms of absolute electricity demand and load shifting potentials due to changing load profiles and requirements.

In the iron and steel, cement and chemicals industries, deep emission cuts require substantial changes but also support for RES and energy efficiency in other sectors and companies (excluding the use of CCS in industry). In the long-term, RES-based use of electricity—either directly or indirectly via secondary energy carriers like hydrogen—can play a more important role, if electricity generation can be provided CO_2-free. However, in order to have new process technologies and innovations ready by 2030, substantial research, development, and innovation activities need to take place in the coming decade. Consequently, the current policy mix needs to be adjusted in order to effectively support R&D activities directed at the decarbonization of industrial production (e.g., ETS-minimum price path, public R&D funding). In general, it is necessary to set incentives toward a low-carbon industry as early as possible to accelerate the market entry of efficient and innovative processes as increases of CO_2 price probably take place after 2040 and consequently affect only a small share of investment decisions taken.

The described technology diffusion in this study leads not only to a higher demand for electricity but also to large flexibility potentials on the demand side. The new potentials exceed the “classical” flexibility options, such as heat pumps and refrigeration, in terms of the shiftable amount of load. However, the number and thus the local distribution of new flexibility options is limited, e.g., the hydrogen electrolysis. Due to their broad diffusion, classic flexibility options could still be a relevant option in low voltage grids to support grid stability. This analysis, though, did not focus on the effect of flexibility deployment in distribution grids.

In order to make use of the future demand side flexibility potential, it is necessary to incentivize flexibility deployment for system stability and renewable integration. A possibility would be the introduction of time-variable electricity prices or to enable the participation of demand side actors in balancing power and flexibility markets.

To conclude, demand side management of the disruptive technologies can contribute to the flexibility needs of RES integration, but requires appropriate regulations. As quite distinct developments of the sector transitions are possible, demand side flexibility contributions should be further investigated for different decarbonization pathways.

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Chapter 8
What is the Flexibility Potential in the Tertiary Sector?

Ulrich Reiter and Martin Jakob

Abstract Demand side management (DSM) is seen as a promising, cost-effective measure to cope with high shares of intermittent renewable energy in the electricity grid system. As the regulatory framework in Europe is changing in favor of opening up new market opportunities for DSM, the question is answered, which potentials are effectively available in the tertiary sector today and in the future. Results in this study are based on empirical data gathered from services companies. The collected data is of high quality and rich in detail and is of utmost importance for relevant model-based analyses. Additionally, the discussed acceptance rates of new technology or behavioral trends have a high impact on the results of the model analyses.

8.1 Introduction

8.1.1 Overview of Demand Side Flexibility Markets

Demand side management is seen as promising, cost-effective measure to cope with high shares of intermittent renewable energy in the grid system. As the targets for renewable energy generation are set, the future potentials and needs for flexibility markets remain currently unclear. One of the main expectations toward the REFLEX project[1] is to shed light on the need of flexibility provision in the future with high shares of renewable electricity generation.

Until recently, the regulatory framework in most European countries was designed in a way that mainly industrial units were able to participate and offer demand flexibility on the wholesale market (Vallés et al. 2016; Dufter et al. 2017). Additionally, in some countries, utilities are able to reduce electricity demand from specific appliances in the residential and services sector to limit demand in certain peak hours

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[1] See www.reflex-project.eu.

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based on local grid codes (Vettori et al. 2017). However, given the need for more flexibility in the future (Alizadeh et al. 2016), the country specific regulatory authorities are obliged to open up the market system for additional market participants (European Parliament and the Council of the European Union 2012).

As the market for DSM from the services and residential sectors are only at their infancy in many European countries (Smart Energy Demand Coalition 2017), the information on the DSM potentials and market acceptance in the services and residential sector is scarce. There is a need to better understand and determine barriers and thresholds, potentials, and drivers, as well as specify a concrete inception of DSM to estimate the full potential of services sector DSM applications.

The process of better understanding the market situation can be supported by the recent development of the technological progress. In recent years, better measurement and control systems have been developed for a facilitated DSM implementation, commonly summarized as smart grids (Behrangrad 2015). By gaining further insights into specific demand profiles from different applications and sub-sector use cases, additional knowledge can be gained on the expectations and boundary conditions from service sector market participants.

8.1.2 Overview of Tertiary Sector and Potential Applications, Regulatory Environment

So far there is an insufficient amount of data available about many areas of the European service sector to define the effective electricity demand (measured hourly and sub-hourly load profiles) and the contemporaneous DSM potential. Although there is some information available on generic load profiles from specific applications (Jakob et al. 2014), only few reports have published the DSM potential from services sector companies and appliances (VDE 2012). In practical terms, it remains unknown which facilities have already been included in DSM markets and what willingness or readiness is dormant in facility operators to govern over specific facilities. Furthermore, it has not been clearly identified which obstacles and restrains are crucial to companies to decide to participate in the DSM market or not.

In order to empirically answer these questions for multiple European countries, a survey directly aimed at companies in the service sector was performed, to determine whether there is potential to increase the share of controllable loads.

This chapter will describe the state of the current aptitude of an implementation of DSM into the tertiary market and explain the implications. Thus, the focal point is laid on research questions concerning sector- and key aspects of an optimized usage of electric power at peak times.

There are several technologies on which DSM would be particularly effective, as they consume, comparatively, large amounts of energy and due to the nature of their functionalities, they are meant to be used for long periods of time. Such technologies comprise air conditioning, cooling, and refrigerating and ventilation systems used in different tertiary sub-sectors such as wholesale or retail trade companies, hotels and restaurants or office-based companies (e.g., Gils 2014; Grünewald and Torriti 2013). As the use and the potential interruption due to DSM of such appliances are usually not process- or income-relevant, and therefore have only limited impact on company operations, they are considered as suitable for DSM application.

In process and economic terms, DSM is considered to be suitable for two types of clients in the services sector: on the one hand side for large companies, which have elevated loads and consumption of electricity in overall terms. Likewise, larger enterprises will have an energy management system (EMS) as well as an energy manager at their disposal and are therefore open to optimize energy demand and related costs. On the other hand, smaller companies with low demand loads and less information on energy demand could be aggregated by service companies, thus making available untapped potentials in a cost-effective manner. However, even companies of large scales may encounter further restrains and obstacles to overcome. Companies generally refrain from change, avoid investments, and fear disturbance of work flow and quality.

Furthermore, there are favorable as well as inhibitory regulatory frameworks which are influencing the take up of DSM in different countries (Smart Energy Demand Coalition 2017). To access and participate in the DSM market, the following main condition needs to be fulfilled (among others): The regulator needs to adjust the market regulations to allow consumer to participate in demand response (DR) programs. Companies need to fulfill various regulations and technical standards to be eligible to participate in the ancillary services market (Arteconi et al. 2012).

As introduced above, the general set-up for this framework on EU level is defined by the Article 15.8 in the European Energy Efficiency Directive (European Parliament and the Council of the European Union 2012). However, looking at country levels, these regulations vary strongly and are not fully implemented yet (Smart Energy Demand Coalition 2017). To get a grasp on the different market statuses, the empirical study was conducted in countries where the market design is at different stages. Whereas in Switzerland and the UK, market regulations for DR options are already in place (Smart Energy Demand Coalition 2017), other countries such as Poland or Germany are lagging behind. In Germany, the Electricity Network Fee Regulation Ordinance (Bundesregierung 2011b) aiming at the avoidance of load fluctuations, incomplete aggregator-models impeding pooling is one of such inhibitory frameworks. Also, the market is not accessible without having to undergo complex qualification processes.

To conclude, currently there are potential cross-sectional technologies at hand, and partial previous experiences from test cases (Klobasa et al. 2006), as well as regulatory facilitating conditions (Bundesregierung 2011a) which allow for increasing DSM participation of service sector companies. Notwithstanding favorable regulatory frames, there is barely space to access DSM's profitable potentials. Only time will show the willingness and readiness at an enterprise level, as well as its practical, usable potentials.

8.2 Data Collection Methodology

8.2.1 Research Questions

To better understand the DSM potential from service sector companies in Europe, an empirical study was implemented to address the following research questions:

- Which technologies of service sub-sectors seem most promising for demand side management?
- Which conditions and barriers affect the realization of the DSM potential in the short- and mid-term?
- What energy efficiency potentials are untapped and therefore indirectly influencing the potential DSM implementation to reduce energy costs of enterprises?
- What expectations are in the market toward returns and profitability of DSM?

8.2.2 Empirical Survey Introduction

A comprehensive survey was designed and addressed toward selected stakeholders from four countries, namely, the UK, Italy, Poland, and Switzerland (see also Reiter et al. 2020). The survey was prepared based on a similar survey already implemented in other projects (e.g., Wohlfarth and Klobasa 2017). This country selection was chosen, as different regulatory environments and their impact on DSM participation are of interest.

The focus of the survey was set on four specific service sub-sectors to include wholesale and retail, hotels and restaurants, private office-type companies, and public administration. Each sub-sector sample contained at least 75 data sets, adding up to 300 data sets at minimum per country. However, due to data availability on potential survey participants and the market structures within the different countries, the number of effective survey participants varies for sub-sector specifications.

In total, 1,200 complete data sets were collected by a specialized contractor using phone interviews and optional online finalization of the survey. With this data set, a first broad overview of DSM potentials in different European countries can be gained. Due to the limited number of samples per sub-sector, the uncertainty of the processed results needs to be considered in the future implementation of such. An overview of the sample sizes is given in Table 8.1.

The survey questions were structured into four different main energy-related categories:

- General information on the enterprise related to energy demand (e.g., energy reference area, annual energy consumption and costs, etc.).
- The enterprises’ relation to energy efficiency (e.g., past or future investments into energy efficiency, energy audits, or similar).

Table 8.1 Overview of sample distribution and number of participants from each service sub-sector

	Bureaus		Public sector	Trade				Hotels/restaurants		Total
Number of enterprises	Private	Public	Health/education	Retail	Wholesale	Of which (food[a])	Of which (non-food[a])	Hotels	Restaurants	
UK	75	39	36	25	51	14	63	40	35	**301**
CH	75	54	22	42	33	16	63	35	40	**301**
IT	75	75	1	7	68	21	58	69	8	**303**
PL	73	56	21	49	26	13	62	43	33	**301**
Total	**298**	**224**	**80**	**123**	**178**			**187**	**116**	**1,206**

[a] Double selection possible

Source Data based on survey results

- Focus on DSM solutions, available technologies, and enterprises' know-how on implementation.
- How enterprises structure their decision processes regarding energy demand and related costs and investments.

From the general information on energy-related aspects of the enterprise, relevant knowledge on the importance of energy demand and costs is gained to derive indicators on relevance and potential clustering for DSM options (see above). Besides information on the energy reference area or the annual energy consumption and costs, further questions were addressing the number of sites and employees, the building standards of the rented or owned premises. Other pressing questions include whether companies are prepared for DSM, i.e., if the electric power usage is metered on hourly or sub-hourly levels, and the type of supply contracts. Both aspects are relevant for DSM implementation in the sense that enterprises need to cope with price signals and related chances and risks for the annual electricity bill.

The second category of questions focused on the enterprises' relation toward know-how on energy demand and energy efficiency. Survey participants were asked, if energy audits were conducted in the recent past and if efficiency improvements were implemented in the past or planned for the near future. As efficiency measures are seen as complementary opportunity compared to demand side management measures to reduce the strain on the electricity grid, the enterprises' commitment in the near future to one or the other will influence the available potential of DSM.

The third category of questions was focusing on evaluating the general acceptance of DSM and available know-how as well as the technological readiness of enterprises toward DSM solutions, and the willingness to install the respective control devices that go alongside with load management. Depending on the use of DSM options already today or not, survey participants were asked about available technologies on site, which of them they already integrated in their DSM contract and which other installations need to be excluded from DSM. To estimate the potential length of DSM measures in terms of temporally shift, companies were also asked about opening hours and times when service interruptions would not be accepted.

Additionally, the economic costs and benefits are of interest for enterprises in the evaluation of DSM participation. Therefore, a set of questions was directed toward expected revenues from DSM participation as well as expected payback times for related investments.

The last category of questions addressed the decision processes of enterprises; to understand the position of the respondent within the firm and which decision levels need to be addressed to realize investments in energy efficiency or DSM. The decision pathway within a company is highly influential on the probability of—and the relevance for implementing DSM measures.

8.2.3 Issues Encountered Regarding Empirical Data

As introduced above, the sample size per country and sub-sector is limited given the available financial resources. Therefore, the significance of the results in terms of statistical analysis could be increased in further work. However, as for modeling purposes and to understand market barriers and drivers as well as to evaluate first DSM potentials, the survey is highly relevant.

As from other empirical studies in the energy sector known (Klinke et al. 2017), the difficulty remains to reach the staff member with relevant know-how on the enterprises' energy topics. Usually, such information on energy managers or similar are not published in organigrams and therefore difficult to collect. By conducting phone interviews, a querist can ask for the relevant person in an enterprise which is increasing the likelihood to collect relevant information for the survey. This approach, however, is limiting the number of potential sample participants as it declines a mass mailing.

8.3 Survey Results and Derived Flexibility Potentials

The results of the stakeholder survey will be explained for all countries in an overview. More detailed results per country can be found under (Reiter et al. 2020). Therefore, the most relevant and telling histograms and results are described and further elaborated upon. Alongside the descriptive statistics, the technological equipment of each of the four surveyed countries are each outlined below and offer a clear insight about how feasible the implementation of DSM is so far and what are potential contributions toward future use of DSM in the services sector.

8.3.1 Participation Interest in DSM

Currently, 58 companies from the survey are participating in DSM which is a participation rate of approximately 5%. In Switzerland, with favorable regulations, the participation rate is slightly higher with 7% overall, whereas in countries with less favorable conditions (e.g., Italy or Poland) the participation rate is in the range of 3.0–3.6%. Interestingly, in all countries, not only large size companies participate in DSM but also small companies with annual electricity consumption below 50–100 MWh per year. In average, 4% (or 26 out of 658) of the companies with an annual electricity demand of below 100 MWh are participating in DSM (cf. Table 8.2). With increasing demand, the share of DSM participants is also increasing. From the companies which estimate their annual electricity demand from 100 MWh up to 1 GWh, 7% are participating in DSM operations and 16% of the companies with an

Table 8.2 Willingness of companies to participate in DSM aggregated for different demand classes

Annual demand (rows) \ Participation in DSM (columns)	Yes		No		I don't know		
	No	[%]	No	[%]	No	[%]	Total number
Below 100 MWh	26	4	600	91	32	5	658
Between 100 MWh and 1 GWh	12	7	149	87	10	6	171
Above 1 GWh	9	16	43	78	3	5	55
Not defined	11	3	263	82	48	15	322
Total	**58**	**5**	**1,055**	**87**	**93**	**8%**	**1,206**

The last column indicates the total number of companies classified in the respective demand category
Source Data based on survey results

electricity demand larger than 1 GWh per year also include DSM operations. Additionally, 3% of the companies which did not specify their annual electricity demand are also participating in DSM operations. However, based on the available answers, it remains unclear why the companies decided to participate in DSM.

From the participants which did not participate in DSM measures at the time of the survey (in total 1,055 respondents), 254 stated that they possibly can imagine to participate in DSM operations in the future (see also next paragraph) and 749 do not see their company participating in DSM and 52 companies remained undecided. The 749 participants which cannot imagine to participate in DSM could indicate which reasons lead to such decision (multiple selection, cf. Table 8.3). Highest risks are evaluated as financial risks with 28.2% (or 211 out of 749 respondents), technical

Table 8.3 Risk perception of companies aggregated for different demand classes for different risk categories

Annual demand (rows) \ Risk categories (columns)	Financial risks high		Technical risks high		Not enough incentives		Sample size
	No	[%]	No	[%]	No	[%]	
Below 100 MWh	112	25	94	21	117	26	**449**
Between 100 MWh and 1 GWh	34	35	34	35	19	20	**97**
Above 1 GWh	6	23	12	46	4	15	**26**
Not defined	59	33	36	20	27	15	**177**
Total	**211**	**28.2**	**176**	**23.5**	**167**	**22.3**	**749**

The column "sample size" indicates the total number of companies classified in the respective demand category
Source Data based on survey results

risks with 23.5% (176 out of 749), and 22.3% (167 out of 749) state that DSM does not provide enough incentives in their view. 215 respondents out of 749 gave additional reasons which were not further grouped.

The results indicate, that the risk perception of mid-sized companies with an annual demand between 100 MWh and 1 GWh is with 20–35% slightly higher in average as compared to small-sized companies with approx. 21–26% (annual demand below 100 MWh) and large companies (annual demand above 1 GWh). However, for 46% of the large companies the technical risks seem to be high which is highly relevant for potential integration into DSM operations. As such companies offer larger DSM potentials due to their energy demand, dedicated measures would be needed to address such risks. Additionally, for 22.3% DSM has too little incentives to be seen as attractive alternative to, e.g., more energy efficiency or doing nothing.

8.3.2 Available Technologies

To derive the DSM potential in the services sector, a distinction is made between the technical potential and the market potential. The technical potential is defined by the installation rate or availability of DSM feasible technologies in companies, including their potential decline in the future. This technical potential is limited not only by the availability (i.e., grid connection), but also the use and importance for the companies' core business. Different owner interests and limitations are of high relevance to understand potential load shifting directions (positive or negative, cf. Michaelis et al. 2017) and shifting hours, during which the demand side flexibility would be available for grid operators. This market potential is further influenced by the willingness of companies to make available such sources to grid operators based on economic considerations (e.g., revenues, risks and chances). In the following, the results of the survey regarding these main aspects will be introduced and explained in more detail.

The technical potential of installed appliances varies strongly between the countries surveyed (cf. Fig. 8.1). The highest numbers of appliances available are cross-sectoral technologies such as ventilation and air conditioning systems. For other appliances such as cooling rooms, freezers, or refrigerators among others, Switzerland seems to have a generally higher equipment rate in general which is almost double as compared to the other countries investigated. From the survey it remains unclear if this is a result of a selection bias (i.e., which companies participated in the survey) or if structural differences between the countries effectively exist. Independent of these considerations, the DSM potential per country and appliance is estimated.

In total, 561 companies stated that their working areas are partially or fully ventilated. From these 561 companies, 429 companies estimate that more than 10% of their total floor area is ventilated. In average, 55% of the floor area is ventilated according to these companies.

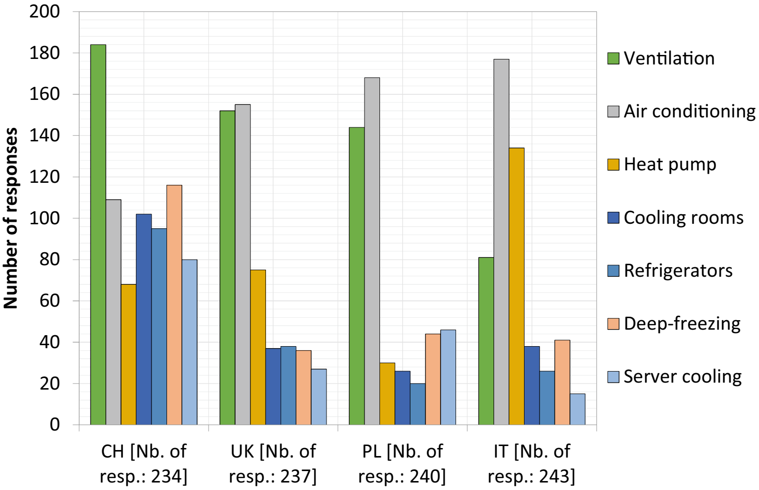

Fig. 8.1 Overview of the number of installed energy demand devices, potentially available for DSM opreation (*Source* Data based on survey results)

Additionally, the number of survey participants allowing for external control of their ventilation system gives an indication on the potential market uptake rate for DSM services per country and sub-sector. From the 561 participants with ventilation systems installed, 87 stated a positive acceptance of external control for their ventilation device in the future and 24 participants stated that their ventilation system is already included in a DSM system. On the other hand, 395 participants denied DSM participation and 55 participants gave no answer. Therefore, additional 15% of the ventilation systems installed, could be included into DSM measures in the short- to mid-term.

The equipment rate of air conditioning systems and heat pumps,[2] offers DSM potential for different seasons and time instances. Demand for air conditioning is largest in summer, often correlating with peaking solar photovoltaic electricity generation (Müller et al. 2019). Therefore, the DSM potential is mainly available in case of applying specific cooling strategies during such periods. Heat pumps in winter can offer upward flexibility (power-to-heat) as well as downward flexibility (load shedding) (cf. Michaelis et al. 2017), in combination with heat storage devices (e.g., heating water tanks) or through the thermal mass of buildings.

In the survey, 609 companies state that they run air conditioning systems on site. From these 609 companies, 332 also include ventilation systems and 108 companies (from 609) run heat pumps. In total, 120 companies run all three devices (i.e., ventilation, air conditioning, and heat pumps) and 188 companies run air conditioning systems and heat pumps on site. Importantly, 251 companies indicate, that the air

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[2] In southern countries (e.g. Italy), heat pumps are often sold as reversible heat pumps and therefore used as heating device in winter and air conditioning system in summer (Nowak and Westring 2018).

conditioning system is a centralized system which is more likely available for DSM operations. With these 251 centralized systems, 222 systems are used to cool more than 10% of the floor area- and in average 58.5% of the floor area of each site. From the 251 centralized systems, 11 systems are already included in DSM operations and additional 39 companies could imagine to opt for DSM in the near future. In total, 20% of the centralized air conditioning systems could be available for DSM in the short- to mid-term.

307 companies indicated in the survey, that they run heat pumps on site for heating or hot water purposes. From these 307 heat pumps installed, 15 systems are included in DSM operations as of today and additional 55 companies indicate that they would allow for external control of their heat pumps to be used in DSM operation. In total, 22.7% of the installed heat pumps could be integrated in DSM operation in the short- to mid-term. Additionally, from the 94 companies which run heat pumps as well as centralized air conditioning systems (see above), only 4 companies opt for external load controls in both systems, limiting the potential for annual DSM operations with such appliances to very small numbers. However, as the potential for operating one of the devices under DSM is higher for either heat pumps or air conditioning systems, it remains open what barriers cause such behavior as from technological and risk perception, similar acceptance rates to combine heating and air conditioning systems in one DSM system are expected.

As more specific devices such as refrigerators or cooling cabinets are not commonly installed in all sub-sectors investigated, the available number of installed appliances is smaller as compared to cross-sectoral appliances introduced above.

In total, 203 companies run cooling rooms, from which 129 cooling rooms are larger than 10 m^2 (max. size is 2,500 m^2 and in average 109 m^2). 10 cooling rooms are already today included in DSM operations, whereas additional 37 companies indicate their willingness to allow for external control in the near future. Therefore, 23% of the cooling rooms would be available for DSM operations in the near future. Additionally, 76 companies indicate that they operator refrigerators connected to a centralized system, from which 8 are already included in DSM operations today and 21 would be potentially available in the near future. Therefore, approx. 38% of centralized connected refrigerators are potentially available for DSM operations. Finally, 96 companies run freezer rooms and 141 run smaller systems such as chest freezers. Approx. 40% of the freezer rooms are larger than 10 m^2 and therefore offer reasonable DSM potential in terms of installed cooling capacity. Two freezer rooms are already operated under DSM system and 12 additional freezer rooms could be available in the near future (approx. 37% of the installed systems). From the 141 smaller freezing systems, 29 systems are connected to a centralized chiller. Three of these systems are already connected to DSM and additional three systems could be connected in the near future. Therefore, 20% of the centralized systems would be available for DSM, however, in overall terms, only a limited potential of freezer units is available for DSM operations.

From the 168 server rooms, 128 are larger than 10 m^2, with reasonable cooling demand. Four of these cooling systems for servers are stated to be included in DSM operations as of today whereas 31 would be available in the near future. Therefore, 27% of such cooling devices could be potentially integrated into DSM operations.

Overall, it was found that reasonable shares of the installed appliances could be made available for DSM operations in the near future due to the willingness of companies to allow for external control of their appliances. The shares of available systems range from 15% of the installed appliances (ventilation) up to 38% (refrigerators).

8.3.3 Derived Flexibility Potentials (S-Curve)

Future load management potentials can be directly linked to the market diffusion of control systems ready for DSM. However, as historic data on such market diffusion is scarce, such technology roll-outs need to be seen in the framework of the higher-level scenario definition. Therefore, to define the potential uptake of DSM ready appliances and their integration into DSM operations, the shares of available DSM systems as of today are used as starting point. Based on the findings above for the additional shares of companies willing to participate in DSM operation and including assumptions on country specific uptake rates of DSM control units as well as exchange rates of non-DSM-ready appliances, so-called S-curves are derived. These S-curves describe the development of installed demand capacity in time which is potentially available for DSM and which is considered in the model exercise to describe the available flexibility potentials and their integration into the market system. These DSM potentials are used as input to the scenario analyses to allow for additional flexibility in the electricity system.

In the REFLEX Mod-RES and High-RES centralized scenarios (cf. Chapter 2) it is assumed that no further incentives or dedicated policy measures are introduced to stimulate the participation in DSM. The share of flexible technologies (referred to as "smart share") is thus mainly dependent on the willingness of companies and households to participate in DSM. In general, the smart share for the flexible appliances in the tertiary sector is deduced from the survey as indicated above. As the model calculations are run on country bases, the country specific uptake is also relevant (cf. Table 8.4).

To adjust for the higher-level scenario definition, different acceptance rates for smart share technologies are applied. In the Mod-RES scenario, in the mid-term, i.e., until 2030, it is assumed that all companies will participate in DSM that are willing to allow an external company to exploit their DSM potential as of today. These are the companies that answered the respective question with "possible," "yes, likely," or "certainly." When other incentives or regulations become available, assuming that in the long-term future, i.e., 2050, all companies will participate DSM that are today not absolutely against an external company exploiting their DSM potential (i.e., also including the companies which answered with "hard to imagine"). With the three data points resulting from the survey, a logistic S-curve could be fitted that reflects the smart share in the different countries for all future years (cf. Fig. 8.2).

Table 8.4 Participation rate of companies already using DSM and willingness of non-DSM users to allow for external control units

	Do you participate in DSM (yes)?	Would allow external access for purpose of DSM?		
	(%)	Yes or likely (%)	No or unlikely (%)	No answer (%)
UK	6	8	78	8
PL	3	25	46	26
IT	4	18	72	6
CH	7	35	51	7

Source Data based on survey results

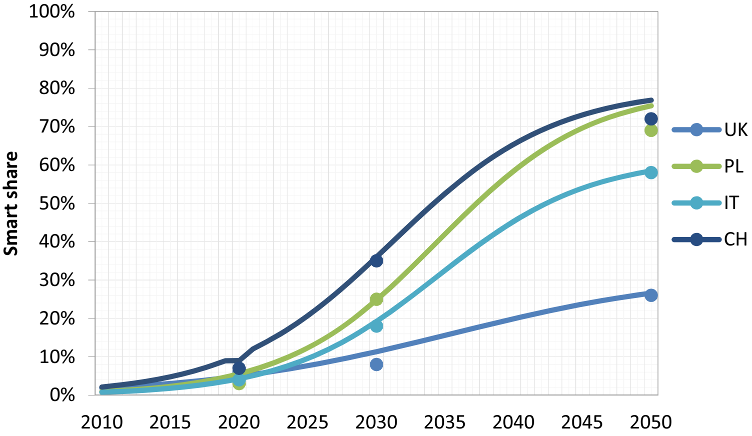

Fig. 8.2 Country specific fitted S-curves for "smart readiness" (*Data source* Fraunhofer ISI and TEP Energy)

For the residential sector, it is assumed that all new installed appliances for which smart control has no effect on performance or consumer comfort, such as heat pumps, will be DSM ready from 2025 onwards. With the diffusion of new installations over time, the smart share increases (cf. Table 8.5).

Table 8.5 Assumed participation in DSM (i.e., "smart share") in the residential sector in the years 2020, 2030, 2040, 2050, based on the diffusion of new appliances/systems

	2020 (%)	2030 (%)	2040 (%)	2050 (%)
Heat pumps	6	25	58	75
Electric vehicles	3	9	22	31
Air-conditioning	3	9	22	31

Data source Fraunhofer ISI and TEP Energy

Table 8.6 Classification of countries regarding their DSM acceptance/participation

Country group	Assigned countries
"high acceptance"	Belgium, Denmark, Estonia, Finland, Netherlands, Sweden, Norway, **Switzerland**
"high potential acceptance"	Austria, France, Germany, Latvia, Luxembourg, **Poland**, Slovenia
"medium acceptance"	Cyprus, Czech Republic, Spain, Greece, Hungary, **Italy**, Portugal, Slovakia, Romania, Bulgaria, Croatia
"lower acceptance"	Ireland, **UK**

In the High-RES scenario, the smart share for all sectors is increased to 99–100%, to align for the higher-level scenario definition. This assumption implies that not only new installations are equipped with smart control systems but also existing installations are retrofitted. Additionally, since empirical data is only available for four countries, country-analogies are used to derive the potential DSM development for all EU-28 countries, Norway and Switzerland (cf. Table 8.6).

Therefore, for each country group, the respective smart share rate is implemented in the model FORECAST (cf. Chapter 3).

8.3.4 Lessons Learned and Issues Identified for Modelers

As for all modelers, the difficulty remains to understand and interpret the given dataset correctly in the way the survey participant has made available his information. There might be open data points or misinterpretations from the survey participant in regard of the questionnaire on the one hand and on the other hand potential over-interpretations of the answers through the modeler. Therefore, one has to be careful, not to derive trends or extrapolations from the dataset which are not accurate or misleading.

A cross-section of market actors for each investigated sub-sector was targeted in terms of size (number of employees) and market profile. Especially the size of the company is of relevance for the project, as for the applied models in the REFLEX project, energy demand projections are linked to such indicator (e.g., energy demand per floor area and floor area per employee). However, information on these indicators from the selected companies is a result of the survey, and therefore, a skewed sample is likely to be achieved, varying across countries. Given the uncertainties due to small sample size and sample structure, in a first approach, no corrections for different size classes were included in the design of the S-curves for DSM potentials. Therefore, further corrections are necessary in terms of sample- and market structure to accurately describe the respective DSM potentials.

Additionally, further assumptions are needed to translate the available technical potential into an applicable DSM potential in the future. With further information and the introduction of pre-installed DSM control units in cross-sectoral appliances such as ventilation or heat pump systems, the use rate of DSM is likely to increase. However, questions and indicators for such trends were not part of the survey and need to be defined by the modelers. Therefore, besides the companies which have indicated their interest in participating in DSM operations in the short- to mid-term, additional potentials need to be estimated and included in the model calculations for the long run until 2050.

8.4 Conclusions and Recommendations for Further Research

With the survey-based approach to collect empirical data on available DSM technologies as well as the readiness of companies to engage in DSM, the basis was set to better understand the DSM potentials from services sector companies.

The empirical study to investigate the DSM potential of services sector companies improves the knowledge base on the availability of suitable DSM devices and the willingness of companies to make the respective appliances available for flexibility needs of the grid. The survey is giving an overview on the current situation of DSM integration which is highly market depending and the perceived risks and opportunities of companies to interact in DSM markets. There is a substantial potential for DSM to be implemented in the near future given the high installation rate of DSM-affine appliances (e.g., heating, ventilation, cooling, etc.). An adequate number of companies can imagine to carry out and benefit from load management, even participating in the financial risks associated with such measures (Reiter et al. 2020). Some more analysis will be carried out on the dataset to fully grasp the potential of the given information as input to the model environment addressed in the REFLEX project.

However, as the sample size can be considered as small for market wide analyses and trend estimates, additional efforts are needed to provide further empirical data on different kinds of DSM aspects in the services and residential sectors.

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Chapter 9
A Techno-Economic Comparison of Demand Side Management with Other Flexibility Options

Theresa Ladwig

Abstract This chapter assesses the techno-economic characteristics of demand side management (DSM) in comparison with other flexibility options (e.g., energy storages) in order to estimate its flexibility and benefit for the system integration of renewable energy sources (RES). The results show that load shedding and load shifting are less flexible than other flexibility options and can therefore only balance short-term fluctuations. In contrast, load increase is more flexible and can integrate excess feed-in from RES also over longer periods. Analysis about the impact of DSM on other flexibility options show, that DSM lowers utilization and contribution margin of peak load plants and energy storages, while it increases both for baseload power plants. More electricity is consumed nationally due to DSM as it decreases imports and exports.

9.1 Introduction

With increasing share of electricity generation from renewable energy sources (RES), the need for flexibility options, which balance intermittent feed-in from RES, rise as well. One balancing possibility is demand side management (DSM). The purpose of DSM is to smooth the (residual) load curve by reducing demand in peak times or increasing demand in off-peak periods. Another aim of DSM is to adapt electricity consumption to electricity generation (Gellings 1985; Behrangrad 2015; VDE 2012; ENTSOE 2017). DSM requires flexible consumers and applications, which can either curtail load during times of peak demand (load shedding), shift load to times of low demand, high RES feed-in (load shifting), or provide additional demand in times of excess feed-in from RES (load increase). Figure 9.1 presents exemplary applications and technologies for each of the three DSM categories.

The paper is based on own analyses which are published in more detail in the dissertation (Ladwig 2018).

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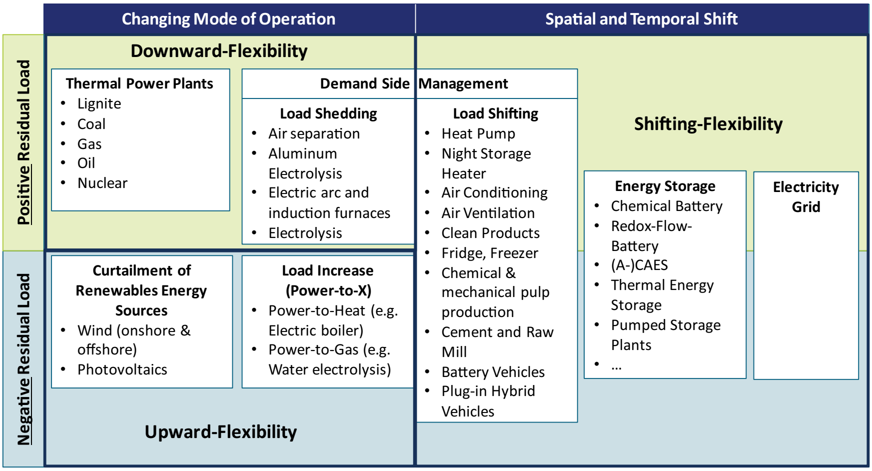

Fig. 9.1 Flexibility options categorized by type of flexibility provision (*Source* Figure adapted and based on Michaelis et al. [2017])

As load shedding applications reduce demand, they are (mainly) applied in times of positive residual load[1] (cf. Fig. 9.1). Thereby, they can reduce the need for electricity generation from thermal power plants. In contrast, load increase applications can balance negative residual load, as they use (mainly) excess electricity generation from RES to produce other energy carriers, e.g., hydrogen or heat. As a result, they can help to minimize or avoid curtailment of excess feed-in from RES. Load shedding applications can balance both, positive and negative residual load. Thus, they can fulfill the same tasks in an electricity system as energy storages and electricity grids.

These examples illustrate, that not only DSM can balance positive and/or negative residual load but also other flexibility options, e.g., thermal power plants or energy storages (cf. Fig. 9.1). DSM applications and flexibility options differ from each other regarding their technical and economic characteristics. Both characteristics determine the need and field of application of a flexibility option for the system integration of RES. Especially the flexibility of DSM is limited to avoid or minimize loss of comfort for the consumers. Therefore, the focus of the paper is to assess the techno-economic characteristics of demand side management in comparison with other flexibility options (e.g., energy storages) in order to estimate its flexibility and benefit for the system integration of RES. For this purpose, Sect. 9.2 presents the main technical and economics characteristics of DSM and compares them to other, competing flexibility options. Section 9.3 presents a model-based scenario analysis, where the trade-off between DSM and other flexibility options at the electricity

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[1] Residual load describes the difference between load and feed-in from RES. It is positive when demand is higher than RES feed-in and negative when demand is lower than RES feed-in.

market is investigated using the example of Germany. The paper closes in Sect. 9.4 with a conclusion, which summarizes the main findings.

The analysis was developed independently of the scenarios (Mod-RES and High-RES). The focus of this supplementary sensitivity is to analyse the potential and meaning of demand side management in an energy system with a high share of renewable energies.

9.2 Techno-Economic Characteristics of DSM in Comparison with Other Flexibility Options

9.2.1 Technical Characteristics of DSM

In order to avoid or minimize loss of comfort for the consumers or production losses in industry, the flexibility and thus the application of DSM are limited by technical restrictions. Main restrictions are:

- *Time of interfere* determines how long the demand of a DSM application can be reduced or increased.
- *Shifting time* needs to be considered for DSM applications of the category load shifting. It presents the maximum of minutes or hours, an electricity demand can be shifted to an earlier or later point in time.
- The *number of interventions* per day, week, month, or year is limited for almost all DSM applications, to minimize loss of comfort as well as production losses.

All three characteristics depend on the underlying process providing DSM. Thus, they can differ strongly between applications. For instance, ventilation and air conditioning systems can only shift their demand for about 1–2 h (as temperature levels have to be kept in a defined range), while heat pumps or electric vehicles show shifting times of about 12–24 h (as the necessary energy services are still guaranteed) (cf. Fig. 9.2). The shifting time strongly depends on the size of the connected storage. Figures 9.2 and 9.3 present the time of interfere and the shifting time for selected load shifting and load shedding applications. They are compared to an alternative and competing flexibility option, to assess their flexibility.

In general load shifting applications compete with energy storages as shifting electricity demand works similar to storing electricity. For instance, both increasing electricity demand as well as charging a storage aims (above others) to use cheap electricity, e.g., in times of excess generation from RES. Furthermore, reducing electricity demand corresponds to discharging a storage as both reduce the (residual) load. In order to investigate the fields of application for load shifting, it needs to be compared with energy storages. As benchmark, Fig. 9.2 presents the pump storage plant Goldisthal (PSP Goldisthal), which is a large and modern pump storage plant in Germany.

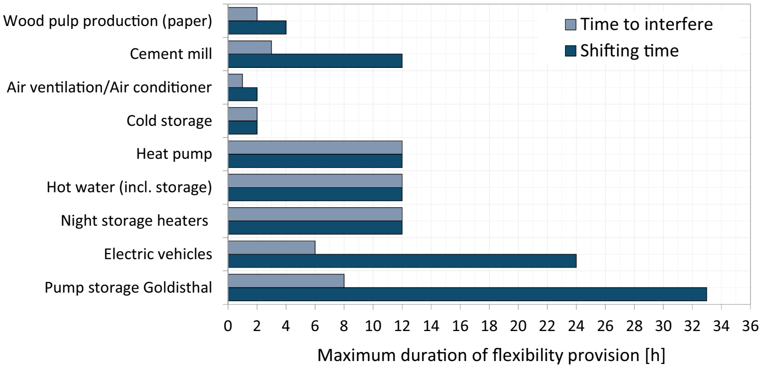

Fig. 9.2 Maximum time of interfere and shifting time of selected load shifting applications compared to the pump storage plant Goldisthal (*Source* Data according to Klobasa et al. [2013], Gils [2014] and own assumptions)

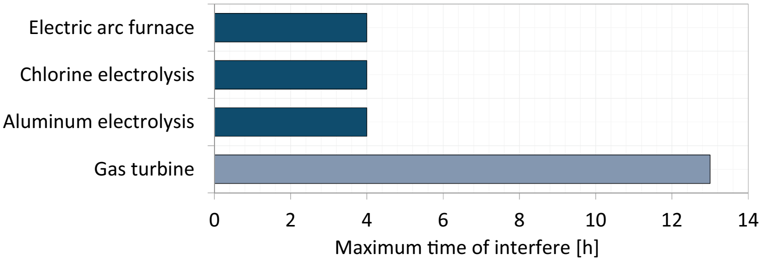

Fig. 9.3 Maximum time of interfere of selected load shedding applications compared to a representative gas turbine (*Source* Data according to Gils [2014] and own assumptions)

As described above, the time of interfere of some load shifting applications are small compared to others. E.g., air ventilation systems can only reduce or increase demand for up to two hours, while load shifting applications with larger storages, such as night storage heaters or electric vehicles, can change their consumption up to 12 h. The PSP Goldisthal can generate electricity for up to 8 h, when the upper storage reservoir is completely drained. Thus, its time of interfere lays in a same range as the one of load shifting applications with large-scale storages. However, the shifting time of PSP Goldisthal is much higher, as the one of load shifting applications. It can store water in its reservoirs over days or weeks (at least from a technical point of view). While load shifting applications have to balance decreased or increased demand within hours. Therefore, load shifting can mainly be used to balance short-term fluctuations of RES feed-in. If low wind periods or periods of excess generation from RES occur for longer time periods, it can only be balanced with large-scale energy storages, such as PSP.

Figure 9.3 illustrates three load shedding applications from industry (aluminum electrolysis, chlorine electrolysis, and electric arc furnace) in comparison with a representative gas turbine. Both, load shedding applications and gas turbines, can be used for balancing load peaks. In case of load shedding applications, they reduce electricity demand in times with load peaks. Gas turbines produce electricity in these times. The time of interfere from industry processes is limited to four hours and the number of intervention is around 40 per year, to avoid (high) losses in production and profits. In contrast, the commitment of gas turbines is (from a technical point of view) only restricted by maintenance work. Therefore, it can produce electricity almost whenever it is needed. As a result, gas turbines are more flexible to balance load (peaks) as load shedding applications.

The presented two options (load shedding and load shifting) aim to decrease or shift demand. The third option in case of DSM is load increase, which consists of power-to-x technologies (PtX). PtX technologies play a major role in the HIGH-RES scenarios investigated in the REFLEX-project. These technologies increase electrification by shifting other energy demands to the electricity sector—so-called sector coupling—and thus contribute to a steeper growth of electricity demand. However, this requires a stronger extension of renewable energies in order to achieve the renewable energy as well as emission reduction targets.

PtX can be used, to consume excess electricity generation from RES. Alternatively, excess electricity generation from RES can be curtailed, when there is not enough infrastructure, e.g., energy storages or electricity grids, to integrate it into the electricity system. Several studies demonstrate, that it is from a system point of view not cost-optimal, to integrate even the last kWh electricity produced (cf. Müller et al. 2013). Therefore, it needs to be investigated, whether it is more cost-efficient to curtail excess electricity generation or to use PtX. With regard to technical restrictions, the time of interfere, and the number of interventions from PtX technologies, such as power-to-heat (PtH) or power-to-gas (PtG), is almost unlimited. It is only restricted with regard to the demand of the produced energy carrier, the plant size (e.g., electrolyzer or boiler) and the subsequent infrastructure, e.g., gas or heating grid. Thus, with regard to these parameters, it is more flexible than load shedding and load shifting. Furthermore, PtX benefits from a high time of interfere and high numbers of interventions. The higher the capacity utilization, the higher is the economic efficiency. In contrast, the longer excess generation from RES needs to be curtailed; the lower is the economic efficiency of the plant. Therefore, RES plants should operate as often as possible. From a technical point of view, their number of activations and time of interfere is only limited by their full load hours. Thus, they show no large differences compared to PtX technologies, with regard to the presented technical characteristics. In order to investigate, which of them leads to a more cost-efficient integration of RES, their costs needs to be analyzed.

The comparison of different DSM applications with competing flexibility options in this Sect. 9.2.1 demonstrate, that load shedding and load shifting applications can only be used to balance short-term fluctuations or load peaks which occur only for short-term periods. If they occur over longer periods, other flexibility options such as gas turbines or (pump storage) plants are needed. Furthermore, the use of these DSM applications is strongly limited by the number of interventions, to avoid loss of comforts for the consumers or loss of production in industry. In contrast, load increase applications, such as PtG or PtH are more flexible than load shedding and load shifting applications. As a result, they can integrate excess electricity generation from RES also over longer periods. However, the commitment of DSM applications is determined by their costs. They are presented and compared to the ones of competing flexibility options in Sect. 9.2.2.

9.2.2 Activation and Initialization Costs of DSM

Costs for using DSM can be divided in two groups: activation and initialization costs. Initialization costs consist of investments and yearly fixed costs. These are mainly investments in infrastructure of measurement, control, and communication technologies. The operation of these technologies leads to yearly fixed costs, which needs to be considered in a cost assessment as well.

Activation costs occur immediately when the DSM potential is used, means as soon as the electricity demand increases or decreases. In case of load shedding applications in industry, they mainly consist of opportunity costs for profits lost. Activation costs of PtX are based on opportunity costs as well. They depend on the prices for the produced energy carriers. For instance, heat is only produced by an electric boiler (PtH), when its production cost is lower than the one of conventional methods (e.g., gas boilers). With regard to load shifting, activation costs represent costs for loss of comfort for the consumers or efficiency losses of underlying storages.

Activation and initialization costs depend on several exogenous factors, such as economic situation (e.g., sales potentials, prices for energy carriers); utilization of production or consumer behavior. Therefore, DSM costs are no fixed number but vary at any time. In addition, it is very difficult to quantify several cost parameters, e.g., comfort losses. Due to these reasons, Table 9.1 presents a range of activation and initialization costs. It shows on the one hand the monetary incentives, which consumers demand for changing their electricity consumption. On the other hand, it indicates the amount of investments to develop the potential. The numbers in Table 9.1 are derived from a system perspective. Therefore, activation costs can take positive and negative values. If it is positive, the consumer gets money for changing the electricity consumption. In case of load increase, additional electricity is consumed to generate heat or gas. It needs to be paid by the plant owner. Activation costs are therefore negative.

Activation costs mainly differ between the DSM categories load shedding, load shifting and load increase, while investment costs strongly vary between sectors. To develop the load shedding and load shifting potential, investments in infrastructure are needed. Most companies of the energy intensive industry in Germany have already an energy management system (Kohler et al. 2010). Therefore, the investments within the industry sector are low compared to the tertiary and residential sector, which show high investment costs due to a missing infrastructure for DSM. The investments for load increase represent costs for new power plants.

Table 9.1 Range of activation and initialization costs for selected DSM applications in Germany from a system perspective

		Activation costs	Initialization costs		
			Investments	Fixed costs	
		[EUR/MWh]	[EUR/kW]	[EUR/kWa]	
Load shedding	Chlorine electrolysis	30–310	1–20^{a}	0–1	Industry sector
	Electric arc furnace	130–1,000			
	Aluminum electrolysis	350–1,500			
Load shifting	Cement mill	0–6			
	Wood pulp production	0–10			
	Fridge and freezer	~ 0	40–1,200^{a}	25–90	Tertiary and residential sector
	Warm water heating	~ 0			
	Night storage heaters	~ 0			
	Air ventilation	~ 0			
	Air conditioner	~ 0			
	Heat pump	~ 0			
	Electric vehicles	~ 0			
Load increase	Power-to-gas	−(16.5–44.9)^{c}	500–1,000^{b}	20–40^{d}	
	Power-to-heat	−(3.3–82.4)^{c}	100–200^{b}	4–8^{d}	

^{a}Investments for infrastructure, ^{b}Investments in the system, ^{c}Excl. statutory dues, ^{d}4% of investments

Source Data according to Langrock et al. (2015), Kohler et al. (2010), Jentsch (2014), and Brunner et al. (2015)

DSM applications show large differences in case of activation costs due to the following reasons. Load shedding applications have the highest activation costs, as they are connected to production losses. The resulting loss of profit needs to be compensated. The profit losses are different for each process, as they depend on the price of the final product or the utilization of the process. Therefore, it is more cost-efficient to decrease the demand of a chlorine electrolyzer than of an aluminum electrolyzer. In case of load shifting, consumers benefit mainly from cost savings, when they consume electricity in times of lower electricity prices. The cost savings from DSM mainly depend on price volatility in the market. No compensation payments as those for load shifting applications are needed. Therefore, the activation costs from a

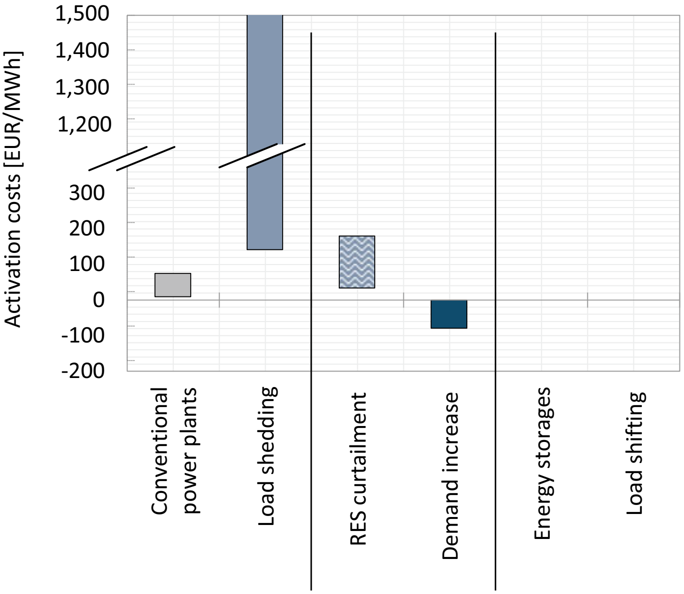

Fig. 9.4 Activation costs of DSM compared to a competing flexibility option (*Source* Data according to Ladwig [2018])

system perspective are nearly 0 EUR/MWh. In case of load increase, activation costs represent payments for electricity consumption. The values in Table 9.1 show the maximum electricity price which can be paid by PtX plant owners, to be competitive to conventional methods. The willingness to pay mainly depends on the sales price of the produced energy carrier.[2]

The activation and initialization costs of each DSM category are compared to competing flexibility options as presented in Figs. 9.4 and 9.5. The category conventional power plants consider gas, coal, and lignite power plants. Initialization costs include the annuity of investment and the yearly fixed costs. Variable costs of electricity generation represent the activation costs, which are fuel costs and costs for CO_2 allowances. The category RES curtailment considers wind onshore, wind offshore, and photovoltaic plants. Activation costs consist of their specific electricity generation costs, which plant owners demand in case of curtailment. Initialization costs consider investments in additional control devices and transaction costs. The category energy storage includes pump storage plants, compressed air energy storages, and lead-acid batteries. Their presented initialization costs consist of plant investments and yearly fixed costs.

Comparing conventional power plants and load shedding, the activation costs of power plants are significantly lower as the ones of load shedding. Consequently,

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[2] Further information about the calculation of opportunity costs for PtX are presented in Ladwig (2018).

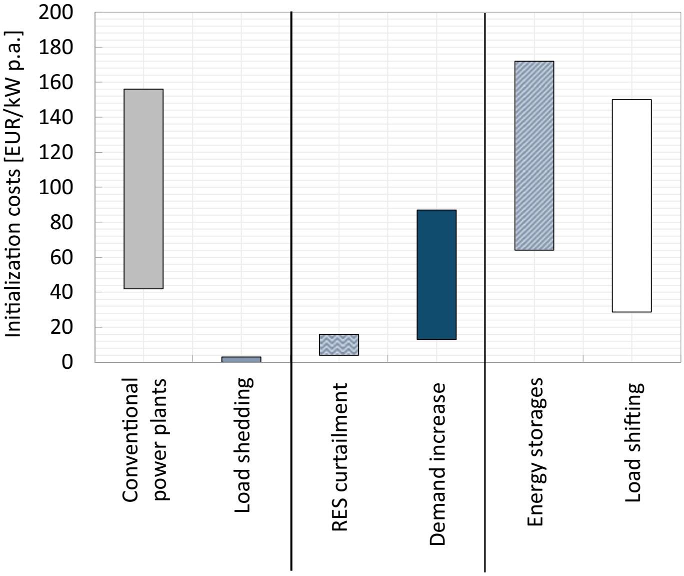


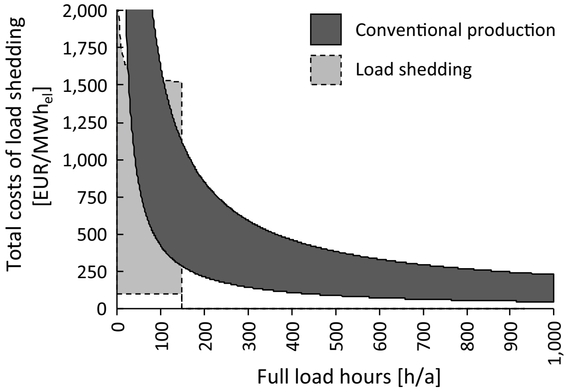
Fig. 9.5 Initialization costs of DSM compared to a competing flexibility option (*Source* Data according to Ladwig [2018])

balancing demand peaks with existing power plants is more efficient than using load shedding. With regard to initialization costs, the picture changes: they are significantly higher for power plants compared to load shedding. Therefore, the commitment of load shedding applications is only cost-efficient from a system perspective, when there is not enough generation capacity from power plants to fulfill the electricity demand. The comparison of RES curtailment and load increase shows similar results, as activation and initialization costs are also contrary. Due to the fact, that activation costs of load increase are negative, they are significantly lower as the ones for RES curtailment. With regard to initialization costs, RES curtailment is more cost-efficient than load increase. Based on the comparison of load shifting and energy storages, the activation and initialization costs fall in a similar range.

The comparison presented above, assesses separately activation and initialization costs. The results show, that either DSM or the competing flexibility option is preferable, depending on considering activation or initialization costs. Both cost components are relevant for a comprehensive assessment. In addition, full load hours need to be considered because the impact of initialization costs on total costs decrease with increasing operation time of a plant or application. Therefore, the following assessment focuses on total costs (including activation and initialization costs) as function of full load hours.

Figure 9.6 presents the total costs as function of full load hours for load shedding in comparison to conventional power plants. The commitment of load shedding is limited with regard to their technical restrictions to avoid (high) production

Fig. 9.6 Total costs of load shedding compared to conventional power plants as function of full load hours (*Source* Ladwig 2018)



losses. Based on the maximum number of activations and time of interfere, they have maximum full load hours of about 160 h per year. In case of low full load hours, the total costs of load shedding are smaller compared to power plants. Consequently, it is more cost-efficient to balance load peaks, which occur for only a few hours a year, with load shedding instead of building a new power plant. In all other cases, power plants are the preferable option.

The comparison of load increase and RES curtailment in Fig. 9.7 demonstrates, that the choice for one option depends on the utilization. From a system perspective it is more cost-efficient to curtail excess RES feed-in, which occurs only for a few hours a year, than building new PtX plants. When excess feed-in from RES occurs for several hours a year, it is more cost-efficient to build and use a new PtX plant, than RES curtailment.

In contrast to the shown comparisons, the total costs as function of full load hours of load shifting applications and energy storages are in a similar range (cf. Fig. 9.8).

Fig. 9.7 Total costs of load increase compared to RES curtailment as function of full load hours (*Source* Ladwig 2018)

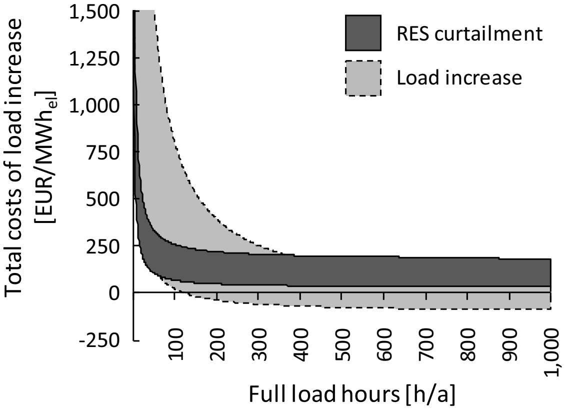
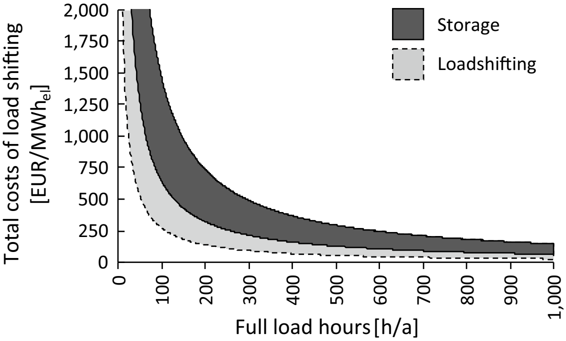


Fig. 9.8 Total costs of load shifting compared to energy storages as function of full load hours (*Source* Data according to Ladwig [2018])



Thus, especially technical restrictions, e.g., availability and shifting time, influence the utilization and the fields of application for load shifting and energy storages.

The presented results are based on comparisons between DSM and competing flexibility options. However, in an electricity system DSM applications also compete with each other as well as with one of the other flexibility options. Especially load shifting applications compete with load shedding and load increase applications as well as with all other flexibility options as they can reduce load peaks and integrate excess RES feed-in. In order to assess the trade-offs and synergies between these options, further analysis with an energy system model is needed.

9.3 Impact of DSM on Other Flexibility Options

9.3.1 Framework of the Analysis

The previous results illustrate very well the technical and economic characteristics of DSM as well as its advantages and disadvantages compared to other flexibility options. However, it does not provide any insights about the trade-offs between DSM and other flexibility options at the electricity market. To investigate the impact of DSM on conventional power plants and energy storages as well as on imports and exports, an electricity market model is applied. The following assessment is performed with ELTRAMOD, which is a bottom-up electricity market model with a temporal resolution of 8,760 h. It calculates the cost-minimal generation dispatch, taking techno-economic characteristics of the generation facilities into account. The present analysis applies a model set-up that differs from the ELTRAMOD version, used in REFLEX. For more detailed information about the model, see Ladwig (2018), Müller and Möst (2018).

The analysis focuses on the German electricity market. But neighboring countries are modeled in an aggregated way as well, to adequately consider imports and exports. Electricity transmission between countries is calculated endogenously by ELTRAMOD. Figure 9.9 presents the model input regarding capacity of conventional

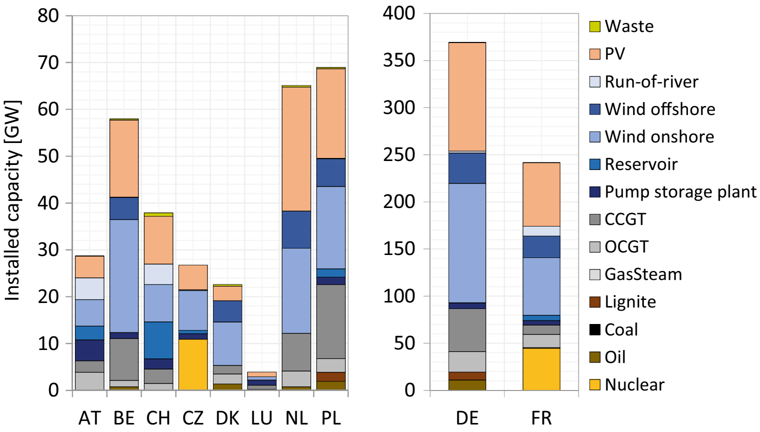


Fig. 9.9 Model input data regarding the capacity of RES and conventional power plants (Source Data according to Ladwig [2018])

Table 9.2 Considered DSM-options in the investigated scenarios

Scenario	Available DSM-options		
	Load shedding	Load shifting	Load increase
Excl. DSM	–	–	–
Incl. 2LS	x	x	–
Incl. DSM-all	x	x	x

Source Own illustration

power plants and RES plants. According to the targets of the German Government, a RES share of 80% is considered.

Three scenarios are investigated (cf.Table 9.2).[3] The first one (*excl. DSM*) is the reference scenario, where no DSM-option is available. The other two differ with regard to load increase. Scenario *incl. 2LS* only considers load shedding and load shifting, while scenario *incl. DSM-all* considers all DSM categories (load shedding, load shifting, and load increase). To investigate the last two scenarios, the potential and the techno-economic characteristics of selected DSM applications are implemented in ELTRAMOD. Table 9.3 shows the respective input parameter with regard to the technical and economic parameter of DSM. Based on the calculations in Ladwig (2018) the following DSM potential was considered:

- Load shedding: 0.9 GW
- Load shifting: 83.9 TWh
- Load increase: 59.0 GW

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[3] As mentioned before, these scenarios are independent from the three REFLEX scenarios (Mod-RES, High-RES centralized, and High-RES decentralized) and should be considered as an additional sensitivity analysis.

Table 9.3 Model input data related to DSM

		Time of interfere	Shifting time	Number of interventions	Activation costs
		[h]	[h]	[–]	[EUR/MW]
Load shedding	Aluminum electrolysis	4	–	40 per year	350
	Chlorine electrolysis	4	–	40 per year	130
	Electric arc furnace	4	–	40 per year	30
Load shifting	Wood pulp production	2	4	24 per year	0
	Cement mill	3	24	40 per year	0
	Fridge and freezer	1	1	<8 per year	0
	Warm water heating	12	12	–	0
	Air ventilation	1	1	<8 per year	0
	Air conditioning	1	1	<8 per year	0
	Heat pump	12	12	–	0
	Electric vehicle	<24	<24	–	0
Load increase	Power-to-gas	–	–	–	Depending on the price for natural gas
	Power-to-heat	–	–	–	

Source Data according to Gils (2014), Klobasa (2007), Langrock et al. (2015), and own assumptions

Further input data (e.g., technical characteristics of power plants, fuel prices, etc.) are presented in Ladwig (2018).

9.3.2 *Impact of DSM on the Operation of Conventional Power Plants and Pump Storage Plants*

At present, especially conventional power plants and PSP balance the intermittent feed-in of RES. For that reason, these plants cannot operate constantly but have to change operation mode depending on the residual load. DSM aims to smooth the residual load curve. As a result, load change activities of conventional power plants should decrease. To analyze this hypothesis, the standard deviation of the residual load and the number of load change activities are assessed. As presented in Table 9.4 the standard deviation of the residual load is about 35% lower, when DSM is applied compared to the scenario without DSM. Thus, DSM flattens the residual load curve.

Table 9.4 Standard deviation of residual load and average number of load change activities of power plants

	Excl. DSM	Incl. DSM-all	Difference
Standard deviation of the residual load (in GW)	26.9	17.4	−35%
Number of load change activities of power plants (incl. PSP)	51,412	30,303	−41%

Source Data according to own calculations

The number of load change activities of conventional power plants decrease as well. The numbers are about 41% lower in scenario incl. DSM compared to the scenario excl. DSM. Consequently, a reduced standard deviation of the residual load due to DSM results in less demand for load change activities of conventional plants.

In addition, smoothing the residual load curve with DSM affects the full load hours of conventional power plants. Figure 9.10 illustrates the change of full load hours, which results from DSM dispatch. It is the difference between the average full load hours per technology class from the scenarios excl. DSM and incl. DSM-all. For lignite, run-of-river and waste power plants the difference is positive, while it is negative for CHP plants and PSP. The utilization of reservoir power plants does not differ between the scenarios, as it runs at full capacity in both.

Figure 9.10 illustrates that using DSM results in higher full load hours for some technologies and minimizes the ones of others. This is due to the fact, that DSM increases demand in times with low or negative residual load and decreases it in times with high residual load (Ladwig 2018; cf. Chapters 6 and 7). Because of the demand increase in times with low or negative residual load, the number of hours with positive residual load raise as well. Base load power plants, such as lignite or run-of-river power plants, profit from this growth. They balance the additional demand, which results from this load increase. In contrast, DSM reduces demand in times with high residual load. Especially peak load plants, such as gas turbines and pump storage plants, operate in these times. As the number of hours and the

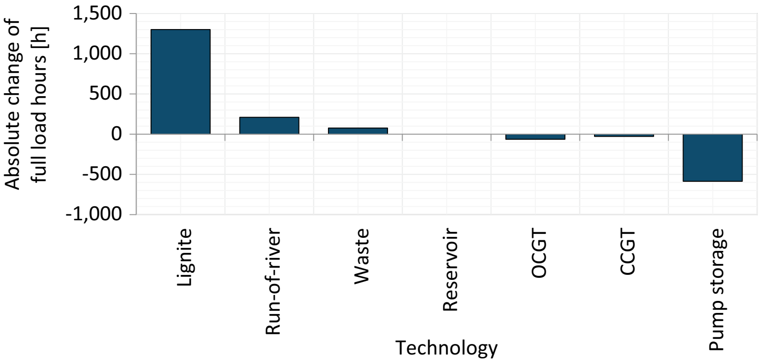

Fig. 9.10 Change of full load hours due to DSM (Source Data according to own calculations)

amount of load peaks decrease with DSM, the utilization of these plants decrease as well. Furthermore, energy storages, such as pump storage plants, profit from high load differences. They store energy in times of low residual load and discharge in times of high residual load. Due to DSM, these differences decrease as DSM reduces demand in times of high residual load and rise demand in times with low or negative residual load. Therefore, the operation of pump storage plants declines. Without DSM average full load hours of about 1,480 h occur, while with DSM the full load hours of pump storage plants are approx. 891 h. This example shows the direct competition between load shifting and energy storages. The round-trip efficiency of pump storage plants is typically about 75–80% (Schröder et al. 2013) due to losses for charging and discharging. The efficiency losses of load shifting are negligible. Therefore, it is from a system perspective more efficient to use load shifting than energy storages. But, the commitment of load shifting is much more restricted as the one of pump storage plants, due to its technical restrictions such as shifting time or number of activations. For that reason, load shifting can only balance short-term fluctuations of the residual load, while pump storage plants can store energy over days or weeks. Consequently, load shifting cannot replace energy storages completely but can reduce the demand of new storage plants.

DSM not only affects the residual load but also the electricity prices. Conventional power plants and storage plants receive revenues from electricity sales on the market. The price changes due to DSM affect the profitability of power plants and energy storages. To quantify this impact, the profit contribution margin of these technologies is assessed. It takes the sales revenues as well as the costs for CO_2 allowances, fuel and load changes into account. In order to compare the results, a specific contribution margin is calculated, which refers to the installed capacity. Figure 9.11 presents the results. It differs between the scenarios incl. 2LS (which considers only load shedding and load shifting) and incl. DSM-all (which considers additionally load increase) because the price level differs between both scenarios. The results from Ladwig

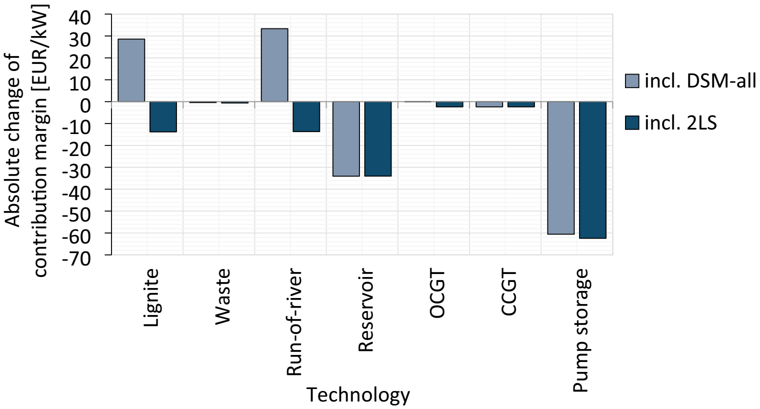

Fig. 9.11 Change of the specific contribution margin due to DSM (*Source* Data according to own calculations)

(2018) show, that load shedding and load shifting reduces the average electricity price, while load increase leads to a higher average price. As a result, the contribution margin of all technologies is lower in the scenario incl. 2LS compared to the scenario excl. DSM.

Reservoir and pump storage plants show the highest differences. Both technologies profit from high electricity prices in times of high residual load, which are reduced by load shedding and load shifting. This negatively affects the profitability of these plants. In addition, load shifting raises electricity prices in times with low or negative residual load. In this way, it makes electricity purchase for charging energy storages more expensive. Besides, the utilization of the plants decrease as presented above. The number of operation hours, when energy storage can earn money, decrease as well. Both effects (lower price differences and full load hours) reduce the contribution margin of pump storage power plants.

The scenario results for incl. DSM-all, where load shedding, load shifting, and load increase are considered, are illustrated in Fig. 9.11 as well. As mentioned before, load increase raises the electricity price in times with low residual load (cf. Ladwig 2018). Especially, lignite and run-of-river power plants profit from this price increase and their contribution margin rises (compared to the scenario excl. DSM). For all other technologies, the scenario results are similar to the scenario incl. 2LS. DSM leads to a lower contribution margin because of the lower prices in times with high residual load, which is caused by DSM.

The presented results show, that the impact of DSM on conventional power plants and energy storages differs: Baseload plants profit from higher demand and prices in times with low or negative residual load caused by DSM. While the utilization and contribution margin of peak load plants and energy storages decrease due to DSM.

9.3.3 Impact of DSM on Imports and Exports

In the following, the impact of DSM on imports and exports using the example of Germany is assessed. For this purpose, the commercial flows of the scenarios incl. DSM-all and incl. 2LS are compared to the scenario results excl. DSM. Figure 9.12 represents the differences, which result for each scenario.

Exports decline in both scenarios (compared to the scenario excl. DSM), while imports increase in scenarios with all DSM-options and decrease in the scenario without load increase. The differences between the scenarios incl. DSM-all and incl. 2LS result from load increase. PtX technologies raise demand in times with low or negative residual load. Therefore, less (excess) electricity is exported to neighboring countries. Furthermore, the additional demand of PtX technologies results in higher imports in some hours. Load shedding and load shifting reduce both, imports and exports, as they lower demand in peak times (when normally electricity is imported) and increase demand in times with low or negative residual load, which causes less exports. In addition, the results from Ladwig (2018) show that the amount of the

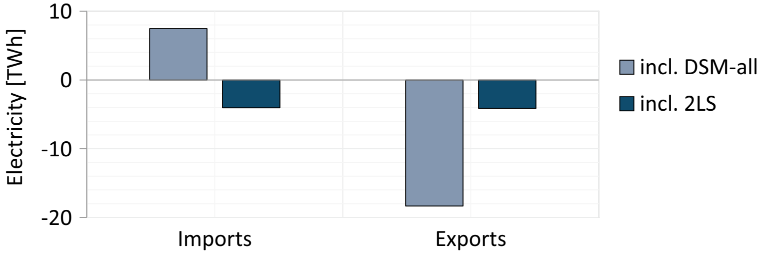

Fig. 9.12 Change of German imports and exports resulting from DSM (*Source* Data according to own calculations)

available DSM potential affects changes in imports and exports as well. The higher the DSM potential, the higher is the effect on the change in exports and imports.

To sum up, due to DSM more excess electricity from RES plants is nationally consumed. In that way, exports are reduced. In times with high residual load, DSM leads to fewer imports. Thereby, it reduces the dependency on electricity supply from neighboring countries in these hours.

9.4 Conclusions

With focus on the techno-economic characteristics from DSM applications, this paper investigates the flexibility of DSM and its interdependencies with other flexibility options, such as power plants and energy storages. DSM is categorized in load shedding, load shifting, and load increase. While load shedding and load shifting can balance mainly short-term fluctuations from demand and RES feed-in, load increase can integrate excess feed-in from RES which occurs over longer time periods.

All three DSM categories compete with other flexibility options. Therefore, the trade-offs to power plants and energy storages as well as to imports and exports are investigated. The results show, that baseload power plants, e.g., lignite power plants, profit from DSM. The reason is, that DSM increase demand and electricity prices in times of low residual load. Therefore, the utilization and the revenues of baseload power plants increase. In contrast, both components decrease for peak load plants, e.g., gas turbines, and pump storage plants due to the smoothing effect of DSM on the residual load and electricity price curve. Especially pump storage plants profit from high temporal differences in residual demand and electricity prices. DSM reduces both differences. Therefore, fewer situations occur, when PSP can charge or discharge their storages. For these reasons, DSM shows the highest impact on the utilization and profit contribution margin of PSP compared to other flexibility options.

In addition, the trade-off between DSM and imports/exports is investigated. Due to DSM, more electricity especially excess feed-in from RES is used nationally.

Therefore, exports decrease. In times with high residual load, imports decrease as well as DSM reduced load peaks. As a result, the national electricity supply is less dependent on electricity generation from neighboring countries in times of peak demand.

Considering all insights, the results show that the commitment of DSM applications is strongly limited by its techno-economic characteristics, e.g., shifting time or activation costs. DSM is in most cases less flexible than other flexibility options, e.g., gas turbines or energy storages. Therefore, a well-balanced mixture of DSM and other flexibility options is needed for an optimal system integration of renewable energy sources. With increasing electrification of demand side sectors or so-called sector coupling, future electricity demand rises, resulting in a growing need for flexibility provided by DSM.

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Part IV
Flexibility Options in the Electricity and Heating Sector

Chapter 10
Optimal Energy Portfolios in the Electricity Sector: Trade-Offs and Interplay Between Different Flexibility Options

Steffi Schreiber, Christoph Zöphel, and Dominik Möst

Abstract The expansion of renewable energy sources (RES) and the electrification of demand side sectors raise the need for power system flexibility. The following model-based analysis illustrates the complexity of the European energy system transformation with pathways regarding the RES expansion, sector coupling, and different levels of flexibility provision. Differences occur concerning the optimal mix of flexibility options between the moderate and ambitious climate target scenarios. Dispatchable back-up capacities are necessary, also in presence of high RES shares. Here, CO_2 prices influence the role of low-carbon technologies. Due to cross-sectoral interactions, energy storages have a limited value. For the ambitious scenarios, the emission reductions come close to the Green Deal targets of the European Commission, while levelized costs of electricity increase moderately compared to the less ambitious scenario.

10.1 Introduction

The power sector is responsible for around 25% of total greenhouse gas (GHG) emissions in Europe (European Commission 2011a). Regarding the overall emission reduction targets, the European power sector has a crucial role since several low-carbon technologies are already technically available at comparably affordable costs (Zöphel et al. 2019). To achieve a cross-sectoral low-carbon European energy system two main challenges arise for the power system. First, future electricity generation will be based mainly on weather-dependent renewable energy sources (RES) (Irena 2018). Balancing requirements will rise as well as electricity supply is becoming increasingly fluctuating. Thus, the former load following power system has to transform into a system, in which both, supply and demand need to be flexible (Müller and Möst 2018). Second, with the electrification of the demand side sectors

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to achieve European energy system-wide decarbonization goals, a significant expansion of low-carbon electricity supply options becomes even more crucial and will strongly influence the transformation of the electricity system (Brown et al. 2018).

Against the background of the energy political aim for decarbonization, the European electricity market plays a decisive role in providing both, the integration of large shares of RES and the provision of electricity for a cross-sectoral energy system (Zöphel et al. 2018). A technology-neutral electricity market is of high importance, since a broad range of flexibility options with different applications including sector coupling technologies exist (Bertsch et al. 2016). Therefore, an optimal mix of these technologies strongly depends on the framework conditions of the energy system, particularly in a cross-sectoral system. Within the REFLEX project, different possible pathways with moderate and ambitious decarbonization goals are developed to analyze the measures required to achieve these targets as well as to improve the understanding of the resulting cross-sectoral interactions. Besides different RES shares, various levels and implementations of sector coupling are therefore examined in the three REFLEX scenarios: Mod-RES, High-RES decentralized, and High-RES centralized (cf. Chapter 2).

From a system perspective, the flexibility requirements arising from the integration of RES as well as from the cross-sectoral electrification are defined by the level and pattern of the residual load (here as difference between electricity demand and fluctuating RES). The techno-economical characteristics of flexibility options enable different applications to balance the residual load. While dispatchable power plants can ramp up and down their electricity generation to provide electricity when needed, storages, demand side management (DSM), and transmission lines provide flexibility by shifting electricity temporally and regionally. Additionally, sector coupling technologies increase the electricity demand and thus raise the use of RES surplus energy (Michaelis et al. 2017). The transformation of the electricity system discussed above as well as the broad range of available technologies lead to complex interactions and competition between these flexibility options, not only within electricity markets, but also cross-sectoral.

The objective of the chapter at hand is to analyze optimal combinations of flexibility options within the REFLEX scenario framework from an electricity market perspective. Therefore, ELTRAMOD is applied, a bottom-up linear optimization electricity market model with model-endogenous investments and dispatch decisions for flexibility options, including various power plants, different types of storage technologies, and different power-to-x applications.[1] Since in the present chapter, the application of ELTRAMOD is embedded in the energy modeling system (EMS) of the REFLEX project (cf. Chapter 3), several model couplings have an impact on the optimal investment and dispatch of the observed flexibility options. With the model-based analysis, optimal combinations of relevant technologies are calculated to assess the role of different flexibility options against the background of the

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[1] Mathematical equations and detailed descriptions of ELTRAMOD are introduced in Zöphel et al. (2019), Hobbie et al. (2019), Ladwig (2018) and Schubert (2016).

scenario-specific assumptions. In a cross-sectoral energy system, interactions with other energy demand and supply sectors are of particular interest.

In the following Sect. 10.2 main assumptions regarding the scenario framework and data input are presented. Furthermore, relevant modeling interfaces with energy system models in the REFLEX EMS are discussed. Thereafter, in Sect. 10.3 the results regarding the optimal mix of flexibility options are analyzed. In addition to the discussion of resulting emission reductions, further insights are given by selected sensitivity analyses. Furthermore, the role of energy storages in the electricity market is analyzed in detail regarding their competition with residential flexibility options. Moreover, the influence of higher RES capacities, to cover the additional electricity demand resulting from sector coupling in the European energy system, is assessed. In Sect. 10.4 the scenario-specific levelized cost of electricity (LCOE) are examined. Based on the results, a discussion and conclusion is formulated in Sect. 10.5.

10.2 Data Input and Model Coupling

The model specifications regarding ELTRAMOD are summarized briefly, since a more detailed model description as well as references to application examples are presented in Chapter 3. The focus of this section rather lies on the input assumptions and underlying model couplings, crucial for understanding the ELTRAMOD results.

ELTRAMOD (Electricity Transshipment Model) is a bottom-up electricity market model. It allows fundamental analysis of the European electricity market. The Net Transfer Capacity (NTC) between regions is considered while the electricity grid within one country is neglected. Each country is treated as one node with country-specific hourly time series of electricity and heat demand as well as renewable feed-in. ELTRAMOD is a linear optimization model, which calculates the cost-minimal investments and dispatch in power plant capacities, storage facilities, and power-to-x-technologies (i.e., power-to-heat, power-to-gas). The set of conventional power plants consists of fossil fuel-fired, nuclear, and hydro plants. Additionally, fossil fuel-fired carbon capture and storage (CCS) technologies are included as low-carbon technologies. Further, flexibility options such as adiabatic compressed air energy storages (A-CAES), lithium-ion batteries, redox-flow batteries, power-to-heat (heat pumps), and power-to-gas applications (electrolyzers) are implemented. Country-specific RES capacities, their expansion pathways and generation in hourly resolution are exogenous inputs for the present analysis. All technologies are represented by different technological characteristics, such as efficiency, emission factors, ramp rates, and availability. Technology-specific economic parameters are annualized capacity specific investment costs, operation and maintenance costs, fixed costs as well as costs for ramping up and down the generation. Additionally, hourly prices for CO_2 allowances and hourly wholesale fuel prices are implemented in ELTRAMOD. The geographical scope covers the member states of EU-27, Norway, Switzerland, United Kingdom, and the Balkan countries.

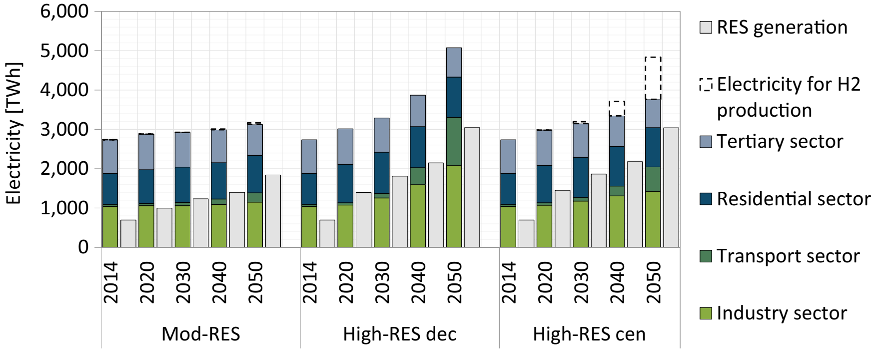

Fig. 10.1 RES electricity generation and electricity demand across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data for the cross-sectoral electricity demand according to own calculations by Fraunhofer ISI with the models FORECAST and ASTRA. Data for RES generation profiles according to own calculations by KIT-IIP as described in Slednev et al. [2018])

Regarding the data input, different levels of renewable electricity generation from PV and wind power are introduced to account for a moderate (Mod-RES scenario) and ambitious (High-RES scenarios) RES expansion pathways until 2050. The RES expansion pathways as well as the respective hourly generation profiles are exogenous model input based on weather data and geo-information on land use (cf. Zöphel et al. 2019; Slednev et al. 2018). Regarding the RES generation, the High-RES decentralized scenario is characterized by a higher share of decentral PV rooftop power plants, while in the High-RES centralized scenario, wind offshore power has higher capacities. In the High-RES scenarios the RES share is calculated based on 80% of the considered countries' electricity demand in the year 2014, resulting in 3,000 TWh (cf. Fig. 10.1).

Within the REFLEX scenario framework the electricity demand is developing differently until 2050, based on the assumed pathways in the energy demand sectors industry, residential, tertiary, and transport (cf. Chapter 6). The interfaces with TIMES-Heat-EU, ASTRA, FORECAST, and eLOAD influence the results of ELTRAMOD. Regarding the electrification of the heat sector, the heat demand for power-to-heat applications is restricted and derived from TIMES-Heat-EU results (cf. Chapter 12). In addition, combined heat and power plant (CHP) capacities, resulting from the model interface with TIMES-Heat-EU, are implemented in ELTRAMOD as minimum fuel-specific power plant installations. Furthermore, there are differences in the developments of the electricity demand and energy efficiency measures between each scenario due to the model coupling with ASTRA, FORECAST, and eLOAD. As illustrated in Fig. 10.1, the scenario-specific assumptions result in a comparably lower electricity system load in the Mod-RES scenario due to lower electrification levels of the energy demand for different end users (e.g., heat, industry, and mobility). Additionally, the REFLEX scenario framework influences the composition of the electricity demand. Besides the direct electricity usage in the industry, residential, tertiary, and transport sectors, the electricity demand for hydrogen production varies between the decentralized and centralized High-RES scenario. In the High-RES decentralized scenario, hydrogen demand for industry and transport is satisfied directly via decentral electrolysis and therefore increases electricity demand in the industry and transport sector. In contrast, in the High-RES centralized scenario, the hydrogen demand is covered model-endogenously in ELTRAMOD via central electrolyzers taking part in the electricity market.

For the scenario-specific model calculations with ELTRAMOD, the total system load is transformed into hourly load profiles smoothed by DSM measures from eLOAD for each scenario. As shown in Chapter 7, the potential of different DSM processes to flatten the residual load can be substantial. Since these applications are assumed to be applied decentralized, thus not participating in the wholesale electricity market, the value of additional market-based flexibility options represented in ELTRAMOD is restricted in the High-RES decentralized scenario.

The varying scenario-specific RES expansion and electricity demand pathways can be summarized when looking at the sorted residual load curves presented in Fig. 10.2. In the Mod-RES scenario (left), the average residual load continuously decreases until 2050 due to the RES expansion, with an increased frequency of low (and negative) residual loads. This development is restrained and reversed in the High-RES scenarios because of the significant increase in electricity demand from different sectors overlapping the RES expansion. As a result of the extensive

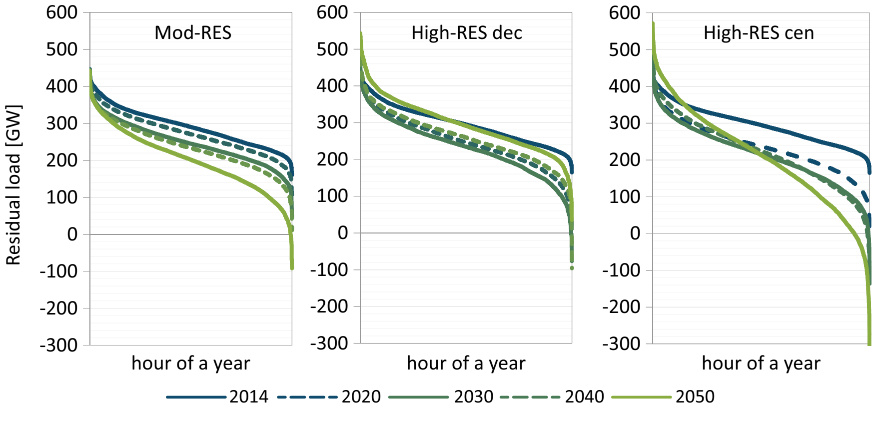

Fig. 10.2 Development of aggregated and sorted residual load curves across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries). The residual load curve is defined as the difference between the system load and the intermittent electricity generation by wind and photovoltaic power plants (Load increase by power-to-gas is not included in the residual load curve of the High-RES centralized case due to the scenario definition. In this scenario, the hydrogen demand is covered model-endogenously in ELTRAMOD via optimal dispatch of central electrolyzers taking part in the electricity market) (*Source* Data according to own calculations. The hourly system load data are model outputs from eLOAD calculated by Fraunhofer ISI. The RES generation profiles are calculated by KIT-IIP as described in Slednev et al. [2018])

application of DSM in the residential sector, this effect is most significant in the High-RES decentralized scenario (middle).[2] In the High-RES centralized scenario (right) the smoothing effect of DSM is lower and thus, the residual duration load curve has a steeper development. As mentioned before and in contrast to the decentralized scenario, load increase by power-to-gas is not included in the depicted residual load curve due to the scenario definition, which defines that the hydrogen demand is covered model-endogenously in ELTRAMOD via central electrolyzers taking part in the electricity market.

Besides the renewable expansion pathways, further central assumptions within the REFLEX scenario framework have an impact on the results presented here (cf. Chapter 2). Of high importance for the modeling results are scenario-specific CO_2 prices reflecting the frameworks discussed in Chapter 2. CO_2 price developments are based on the EU Reference Scenario (Capros et al. 2016). Further information on model input data can be found online at the REFLEX database.[3] The input regarding the fuel and CO_2 prices as well as the cost developments based on the technological learning curves strongly influence the model-endogenous decisions on optimal flexible technology combinations. Additionally, existing power plant decommissioning is assumed to be exogenous, based on power plant age.

10.3 Optimal Investments in Flexibility Options

Since the results regarding the sector coupling technologies are influenced by the cross-sectoral electricity demand for district heat (power-to-heat) and hydrogen (power-to-gas) within the REFLEX model coupling framework, the model-endogenous investments are largely restricted and the results for these technologies are presented first. More detailed analyses are presented regarding the power plant and storage investments, with additional sensitivity analyses in Sect. 10.4. In general, the results are depicted on an aggregated level for the energy systems of the EU-27, Norway, Switzerland, United Kingdom, and the Balkan countries.

10.3.1 Sector Coupling Technologies

Ideally, increased demand from sector coupling technologies coincide temporally with surpluses of RES electricity generation. From an electricity market perspective, heat pumps or electrolyzers for instance, may improve RES integration by

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[2] The speed of RES expansion and electrification of demand side sectors have a substantial influence on the development of the residual load curve. In REFLEX, a range of different residual load curves is analyzed to assess the impact of different future developments. Results can be transferred depending on the developments in the real system.

[3] https://data.esa2.eu/tree/REFLEX.

smoothing and increasing the residual load. During times with high RES feed-in and low electricity prices, a dispatch of power-to-x technologies to substitute intra-sectoral fuels is most economical. Nevertheless, these applications are restricted by the availability of infrastructure (e.g., heat storages for heat pumps and electric boilers or hydrogen storages and pipelines for electrolyzers), but also by required full load hours to cover investment costs (Brunner et al. 2015). Despite techno-economic challenges, ambitious climate protection goals may increase the need for electricity-based substitutions of carbon-intensive fuels in different energy sectors. This energy policy-driven fuel switch is normatively described in the REFLEX scenarios and results in the assumptions described in the sections before. In the following, the electricity market-based optimal investments in power-to-x technologies are compared with those calculated for other sectors (cf. Fig. 10.3). For the district heat sector, heat pumps and electric boilers are the technologies included.

High shares of residential heat pumps (as a result of eLOAD calculations, cf. Chapters 6 and 7) can be observed, particularly in the High-RES decentralized scenario. Regarding the district heat systems, electric boilers have the highest capacities (cf. Chapter 12), particularly in the centralized scenario, since heat pumps are less beneficial due to higher specific investment costs. As a consequence of the higher heat demand in the High-RES centralized scenario, the overall power-to-heat capacities are the highest with around 300 $\mathrm{GW_{el}}$. These power-to-heat technologies are equipped with heat storages (cf. Chapter 12) and can be dispatched flexibly, mainly to enable the use of high RES feed-in phases (low residual load) with low electricity prices. The average power-to-heat full load hours are below 1,000 h/a.

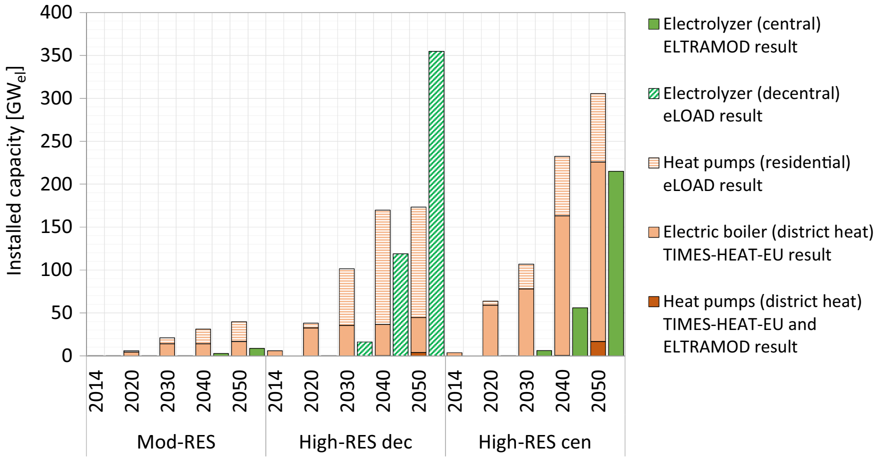

Fig. 10.3 Installed power-to-heat and power-to-gas technologies across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by Fraunhofer ISI, AGH University Krakow, and TU Dresden with the models eLOAD, TIMES-Heat-EU, and ELTRAMOD)

While in the Mod-RES scenario there is only a small demand for hydrogen, from 2030 on, the demand increases significantly in both High-RES scenarios. As mentioned before, the hydrogen provision for industry and transport varies between the decentralized and centralized scenario. The decentral onsite production requires around 350 GW_{el} electrolyzer capacity in the High-RES decentralized scenario (cf. Chapters 6 and 7). The optimal capacity for the central hydrogen production to cover the exogenous hydrogen demand in the High-RES centralized scenario is calculated model-endogenously with ELTRAMOD. In total, 200 GW_{el} are installed. The results show average full load hours of the electrolyzers above 6,000 h/a illustrating the high specific investment costs for large-scale electrolyzers, which needs to be compensated by achieving high utilization rates. For the same reason, additional investments in hydrogen storages cannot be observed. Therefore, the dispatch of electrolyzers is rather inflexible.

10.3.2 Power Plant Mix

With total electricity generation capacities increasing up to 690 GW in the Mod-RES scenario and up to 1,100 GW in the High-RES scenarios, weather-dependent wind and PV power plants become the dominating electricity generation technologies in each REFLEX scenario. Dispatchable power plants enable the electricity provision in times when the feed-in of the fluctuating energy sources cannot satisfy electricity demand.

In Fig. 10.4, the model-endogenously added power plant capacities are presented together with the exogenously determined RES installations (cf. Section 2). In total, the High-RES decentralized scenario shows the highest power plant capacities (around 2,000 GW) due to the lower capacity credit, i.e., availability of PV, and higher electricity demand in this scenario. Furthermore, both the low capacity credit of the RES as well as the increasing electricity demand result in the need for additional dispatchable power plants. In each scenario, the fossil fuel-based capacities are decreasing until 2030 and 2040, respectively, while there is an increase until 2050 resulting from sector coupling.

In total, there are more fossil fuel-based technologies in the High-RES scenarios compared to Mod-RES scenario due to the higher (additional) electricity demand resulting from the sector coupling. Ensuing from the increasing CO_2 prices, a fuel switch from emission-intensive to low-carbon technologies can be observed in the optimal power plant mix until 2050. Within the conventional power plant capacities, gas-fired plants achieve the highest shares, but also nuclear power plants remain an option (between 43 GW and 65 GW across all scenarios), despite relatively high investment costs. Furthermore, there is no final phase-out from coal and lignite, mainly due to must-run CHP capacities for the district heat sector. From 2040 on, CCS gains importance in the generation mix of the High-RES scenarios due to high CO_2 prices and the corresponding need for emission reduction. In the High-RES decentralized scenario, around 203 GW of gas-fired CCS technologies are installed,

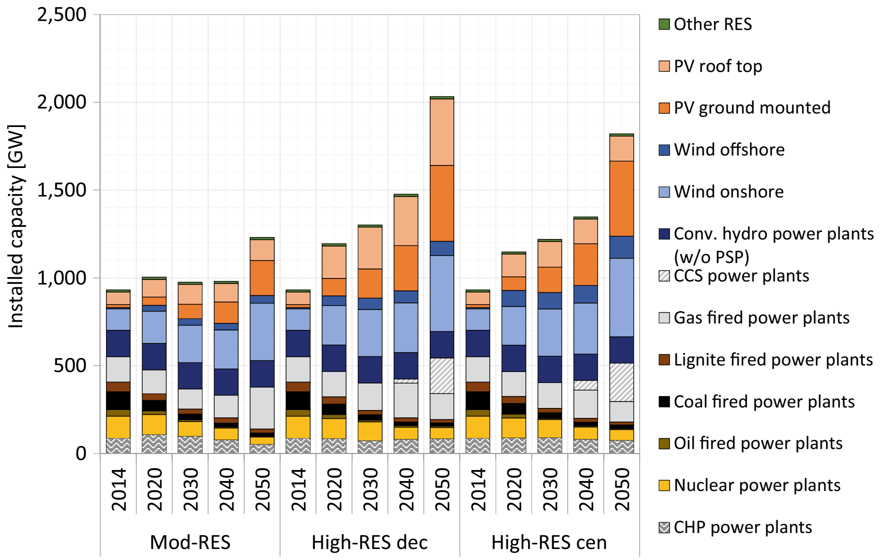

Fig. 10.4 Installed electricity generation mix across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying the model ELTRAMOD)

whereas in the centralized scenario optimal investments account for 218 GW. As mentioned in the model description in Chapter 3, the investment in new nuclear power plants is restricted to countries, where specific plans for new nuclear power plants exist (e.g., United Kingdom, Poland, and Hungary). This assumption increases the value of alternative low-carbon technologies like CCS to cover the additional electricity demand. In total, the aggregated results for nuclear and CCS-based power plants in the High-RES scenarios are in the range of existing studies, but those often show higher shares of nuclear power plants compared to CCS. For instance, compared to the EU Roadmap (European Commission 2011a), 120 GW of installed capacities for nuclear power plants and 160 GW for CCS plants are estimated. In the EU Reference Scenario, around 93 GW nuclear power plants and 19 GW CCS technologies are installed until 2050 in the European energy system (Capros et al. 2016).

As mentioned before, with increasing CO_2 prices as data input, the emission reduction targets within the REFLEX scenario framework are implicitly considered. Figure 10.5 shows the development of the CO_2 emissions until 2050 for each scenario in the electricity sector, based on the dispatch of the power plant mix presented before. CO_2 emissions decrease significantly in all scenarios and are higher in the Mod-RES scenario compared to the High-RES scenario due to larger shares of generation technologies with higher CO_2 emission factors. In the decentralized scenario, more CO_2 is emitted compared to the centralized scenario because of more carbon-intensive electricity generation caused by higher electricity demand (cf. Fig. 10.1) and lower RES capacity credits within the PV dominated decentralized system. The increase

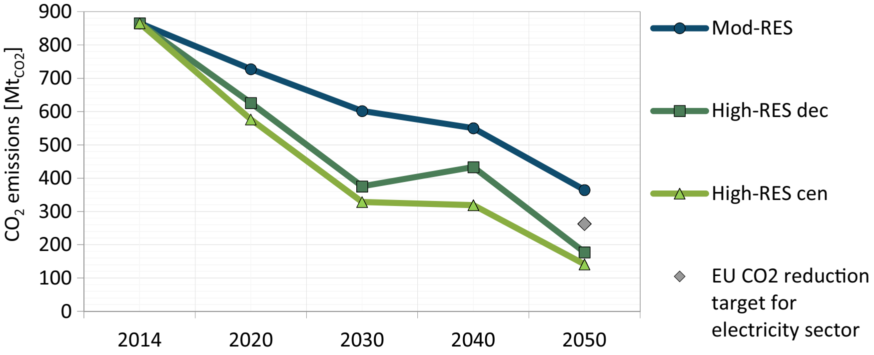

Fig. 10.5 Development of total CO_2 emissions in the electricity sector across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying the model ELTRAMOD)

of CO_2 emissions by 2040 in the decentralized scenario results from the increase of electricity generation from closed-cycle gas turbines (CCGT) due to higher electrification of demand side sectors compared to the centralized scenario. The further decrease of CO_2 emissions by 2050 results from the gas-fired technology switch from CCGT to gas-fired CCS generation. The approximately estimated CO_2 reduction target of the EU (European Environment Agency 2019) for the electricity sector is about 236 Mt_{CO2}, which is achieved in both High-RES scenarios.[4]

10.3.3 Storages

An economic potential for storage technologies in the electricity market only arises, when the residual load is fluctuating between high and low phases, resulting in hours with high (discharging storage plant) and low (charging storage plant) electricity prices. By temporarily shifting electricity generation and demand, storages theoretically compete with power plants, particularly in the presence of higher RES shares (Zerrahn and Schill 2017; Zöphel and Möst 2017). As shown in Sect. 10.2, although the RES share is rising, the substantial increase in electricity demand, resulting from sector coupling particularly in the High-RES scenarios, rarely leads to low or even negative residual loads. In the following, the influence of these cross-sectoral interactions is analyzed in detail.

In Fig. 10.6, the outcomes based on ELTRAMOD regarding the storage technologies are presented together with the results from eLOAD (namely residential PV-battery systems) to compare the capacities across sectors (cf. Chapter 7). Although

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[4] More ambitious CO_2 emission reduction targets have been agreed with the European Green Deal, and most likely the power sector will also receive a more ambitious sector-specific CO_2 emission reduction target, although this has not yet been officially defined.

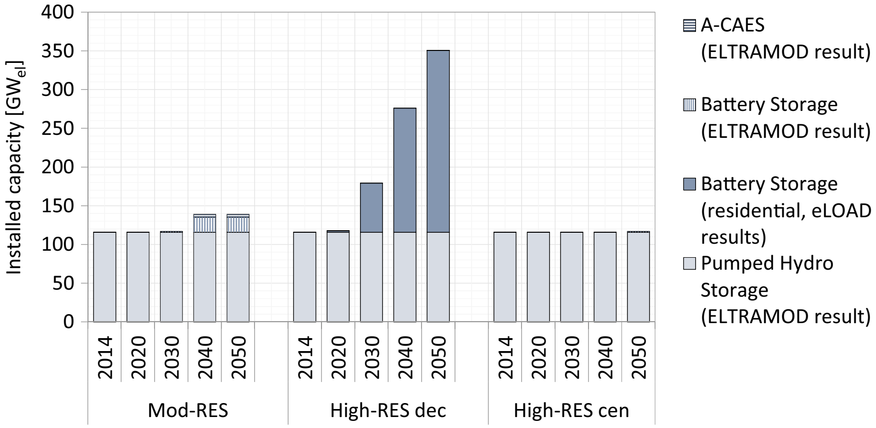

Fig. 10.6 Installed storage capacities across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by Fraunhofer ISI and TU Dresden with the models eLOAD and ELTRAMOD)

batteries from electric vehicles (EV) have a storage capacity, there is no vehicle-to-grid technology assumed in eLOAD, thus only a shift of the charging time is possible. Therefore, EV storages are excluded in Fig. 10.6. Besides the existing but not expansible pump storage plant (PSP) capacities accounting for around 120 GW, significant electricity market-based investments in additional storage capacities can only be observed in the Mod-RES scenario, where small lithium-ion batteries (around 18 GW) and to a lesser extent adiabatic compressed air energy storages (A-CAES) (4 GW) are installed. This reflects the comparably higher variability of the residual load, since the electricity system load curve is less flattened by decentral DSM measures. In the High-RES decentralized scenario, residential PV-battery systems are dominating the storage mix. Nevertheless, their application is to increase residential self-consumption, resulting in a flattened overall residual load. Whereas, in the centralized scenario the load curve is smoothed to a lesser extent by flexible loads (cf. Fig. 10.2). Furthermore, the high intermittent wind shares in the centralized scenario increases the potential for spatial compensation effects which leads to an increasing importance of electricity grid expansion.

In addition to the smoothing effect of the residual load by storages and further DSM measures in the residential sector, sector coupling increases the residual load from a residential (e.g., local heat pumps) and system (district heat pumps, power-to-gas) perspective, particularly in times with negative residual loads. Therefore, missing surplus phases and arbitrage applications decrease the value of electricity market-based storage investments and result in low additional model-endogenous storage capacities.

10.4 Sensitivity Analyses

To further assess the cross-sectoral interaction of electricity market-based storage investments with DSM measures (including PV-battery systems), a sensitivity analysis with no assumed DSM potential on residential level is described in the following Sect. 10.4.1. Additionally, a cost reduction in battery storages and its impact on storage investments is investigated. A further sensitivity analysis is applied in Sect. 10.4.2 to determine the impact of higher weather-dependent RES shares on the mix of flexibility options discussed before.

10.4.1 Impact of Limited DSM Potential and Reduced Battery Investment Costs on the Storage Value in the Electricity Market

The sensitivity analysis is applied for the High-RES scenarios, since here the strongest effects are expected. In Fig. 10.7 the sorted residual load curves with and without DSM measures as well as for the reference year 2014 are compared for each the decentralized and centralized scenario.

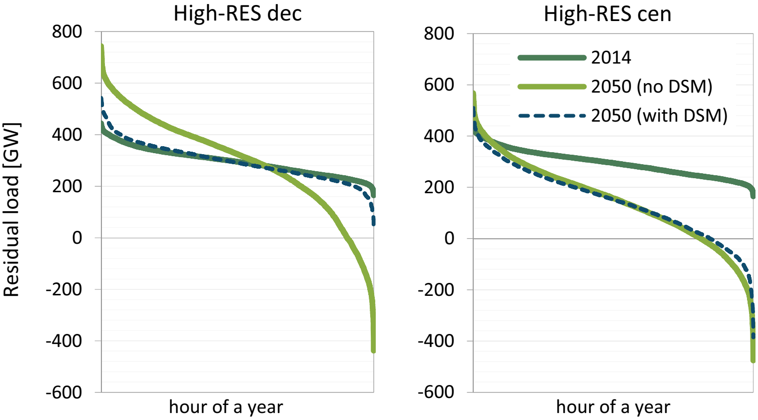

Fig. 10.7 Sorted residual load with and without smoothing effect of DSM applications across all modeled countries (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) in 2050 compared to 2014 (The optimal dispatch of central electrolyzers is an ELTRAMOD model result [not an input parameter, therefore not considered in Fig. 10.7] leading to load increase mainly in hours with low or even negative residual load in 2050 [with DSM], resulting in a similar development of the smoothed decentralized residual load in 2050 [with DSM]) (*Source* Data according to own calculations. The hourly system load data are model outputs from eLOAD calculated by Fraunhofer ISI. The RES generation profiles are calculated by KIT-IIP as described in Slednev et al. [2018])

While in both scenarios, the electricity demand is increasing until 2050, the differences between the decentralized and centralized scenario framework regarding the deployment of DSM measures become obvious in Fig. 10.7. The extensive application of DSM measures in the decentralized scenario results in a smoothed residual load similar to the curve of the year 2014 (cf. dark green and blue dashed line). Without exploiting this DSM potential, the curve becomes steeper with more extreme positive and negative peaks. Additional to the stronger use of the DSM potential, this scenario is characterized by decentral hydrogen production resulting in an overall increased residual load. In contrast, the flexibility potential of hydrogen electrolysis in the centralized scenario in the transport and industry sector is not included in the bundle of DSM applications as it is in the decentralized scenario. Furthermore, a comparatively low DSM potential is assumed in the model due to lower societal acceptance for e.g., electromobility, PV-battery systems, heat pumps in the residential and tertiary sector (by assumptions). As mentioned before, the central electrolyzers directly participate in the electricity market in the centralized scenario. Therefore, the investment and dispatch decisions regarding central electrolyzers are a model-endogenous result from ELTRAMOD. This leads to a steeper sorted residual load in the centralized scenario with only small differences between the residual load curve with and without the smoothing effect of DSM for the year 2050.

In an additional sensitivity analysis, specific investment cost reductions by 50% are assumed for the four battery storage types (small, medium, and large lithium-ion and redox-flow) based on the derived learning curves (cf. Chapter 4). Table 10.1 compares the assumed specific investment costs for these storage types for the year 2050.

Figure 10.8 shows the results regarding the model-endogenous installed conventional capacities (left ordinate) and storages (right ordinate with different axis scaling) including pump storage plants, adiabatic compressed air energy storages as well as battery storages. With reduced investment costs, additional batteries are installed in 2040 and 2050 (mainly redox-flow batteries), particularly in High-RES centralized.

Table 10.1 Specific investment costs and cost reductions for battery storage technologies in 2050

	Storage capacity	Specific investment cost in 2050	Specific investment cost with 50% reduction in 2050
	[MWh/MW]	[1,000 EUR/MW]	[1,000 EUR/MW]
Small lithium-ion battery	1	199	100
Medium lithium-ion battery	4	694	347
Large lithium-ion battery	10	1,684	842
Redox-flow battery	10	752	376

Source Data based on learning curves from Louwen et al. (2018) and Chapter 4

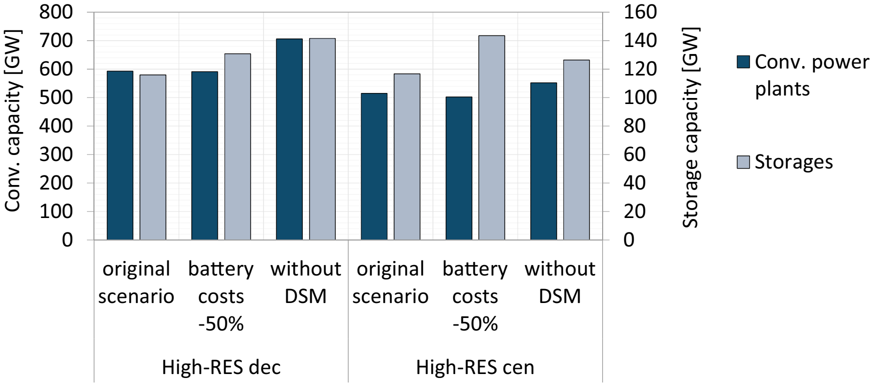

Fig. 10.8 Impact of reduced specific investment costs for storages and no DSM measures on the capacity expansion of conventional power plants and storages across all modeled countries in 2050 (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying ELTRAMOD)

Regarding the competition with the conventional power plants, Fig. 10.8 shows that only a small amount of conventional capacities can be substituted in both High-RES scenarios. Nevertheless, this effect is higher in the centralized scenario since the structure of the residual load curve (with DSM measures) is more suitable for (centralized) storage applications. As a result, in the High-RES centralized (decentralized) scenario a storage investment cost reduction by 50% leads to overall additional storage capacities of 27 GW (15 GW) and conventional capacity reductions of 12 GW (1 GW).

Furthermore, for the sensitivity without DSM measures an increase of fossil fuel-based capacities can be observed, since the residual load peaks are increasing significantly, particularly in the decentralized scenario. Additionally, the storage investments are increasing as well. In general, reasons for the low battery storage investments in each sensitivity is the high electrification in other sectors and the competition with power-to-x technologies, particularly for times with low residual loads. The results also show an increase of curtailed RES electricity due to the missing application of DSM. Similar interactions are discussed in the literature (e.g., Müller and Möst 2018). While in the centralized High-RES scenario the RES curtailment increases from 23 TWh (with DSM) to 37 TWh (without DSM), this increase is more pronounced in the decentralized scenario with 0.2 TWh (with DSM) to 43 TWh (without DSM). Nevertheless, the overall curtailment of RES is marginal and below 2% of the electricity generated by RES.

10.4.2 Impact of Higher Shares of Renewable Energy Sources

A further sensitivity analysis is applied to investigate the impact of higher weather-dependent RES shares on the mix of flexibility options discussed before. This is also done because the original RES shares in the REFLEX scenarios are calculated based on the European electricity demand of the base year 2014. With the cross-sectoral electrification of energy demand, the electricity demand in the High-RES scenarios increases from 3,000 TWh to more than 5,000 TWh in 2050. Therefore, electricity generation from wind and PV power plants has to increase to around 4,000 TWh (5,000 TWh) to theoretically cover 80% (100%) of this electricity demand. For this sensitivity analysis only the High-RES scenarios are considered to focus on the ambitious RES development pathways, the scenario-specific installed wind and PV capacities are linearly scaled-up for each country.

Table 10.2 illustrates the resulting capacities for the year 2050. The overall installed RES capacities of 1,325 GW (decentralized) and 1,143 GW (centralized) cover around 55% of the electricity demand in the year 2050 in the original scenarios including electricity for sector coupling. In 2019, approximately 573 GW of renewable capacities are installed with a resulting RES share of approximately 45% of total electricity consumption and 20% of gross final energy consumption in the considered countries (Irena 2020). These numbers illustrate the effort still necessary to achieve these high shares of renewables in 2050 by taking sector coupling into account. In the High-RES decentralized scenario, these values have to increase to 1,965 GW and 2,512 GW to achieve a RES share of 80 and 100% on electricity consumption, respectively. Again, due to the higher shares of wind power plants and their higher availability, the required capacity expansion in the centralized scenario is lower and amounts to 1,586 GW (80%) and 2,029 GW (100%).

Table 10.2 Installed wind and PV capacities in the original scenarios and in the sensitivities across all modeled countries in 2050 (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries)

Installed capacities [GW]	High-RES decentralized			High-RES centralized		
	Original	80% RES share	100% RES share	Original	80% RES share	100% RES share
Wind onshore	432	641	820	447	623	797
Wind offshore	82	119	152	125	169	216
PV ground mounted	433	643	823	428	595	762
PV rooftop	378	561	718	143	199	254
Total	**1.325**	**1.965**	**2.512**	**1.143**	**1.586**	**2.029**

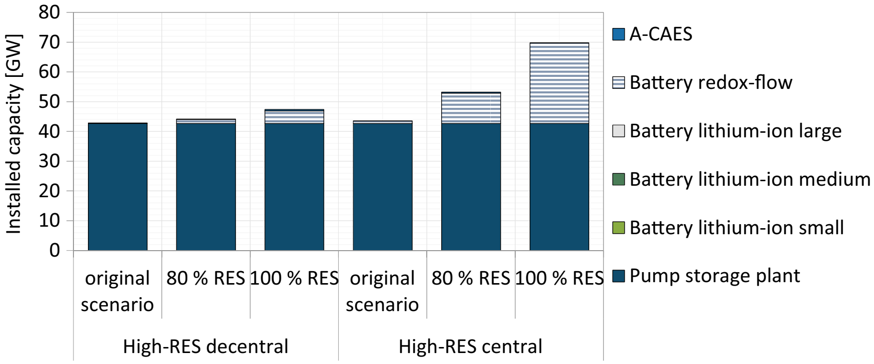

Fig. 10.9 Impact of higher RES shares on investments in storage capacities across all modeled countries in 2050 (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying ELTRAMOD)

With these wind and PV capacities and the respective electricity generation, optimal investments and dispatch in conventional power plants, storages and power-to-x technologies are model-endogenously calculated with ELTRAMOD, while all other input data and assumptions remain unchanged. The results show that for each scenario conventional, thus dispatchable capacities are still necessary to cover the positive peak residual load. Nevertheless, in both High-RES scenarios the aggregated capacities are decreasing from more than 500 GW in the original scenario to around 440 GW with an 80% RES share and to around 400 GW with a 100% RES share. Since the residual load curve is characterized by more very low and negative hours, storages become more valuable with increasing RES shares and can substitute power plant capacities.

Figure 10.9 shows the storage capacities for the year 2050 with different RES shares. In the High-RES centralized scenario, the additional storage capacities are highest with up to 27 GW (100% RES share), since the residual load is steeper. In general, redox-flow batteries are installed, mainly to balance short-term fluctuations.

It becomes obvious that dispatch of power plants mainly covers periods with high residual load, when analyzing the aggregated electricity generation and demand in the different sensitivities for the year 2050 (cf. Fig. 10.10). Compared to the original scenario, fossil fuel-based (conventional) electricity generation is reduced by 70–75% at a RES share of 100% in both scenarios. Analyzing the CO_2 emissions, the higher RES shares from 80% and 100% (without curtailment) lead to further emission reduction up to 82% and 74% in the decentralized and centralized scenario, respectively, compared to the original scenario results. Nevertheless, also the curtailed amount of wind and PV electricity is increasing up to 12% of total RES generation, thus decreasing the effective RES share to around 90%.

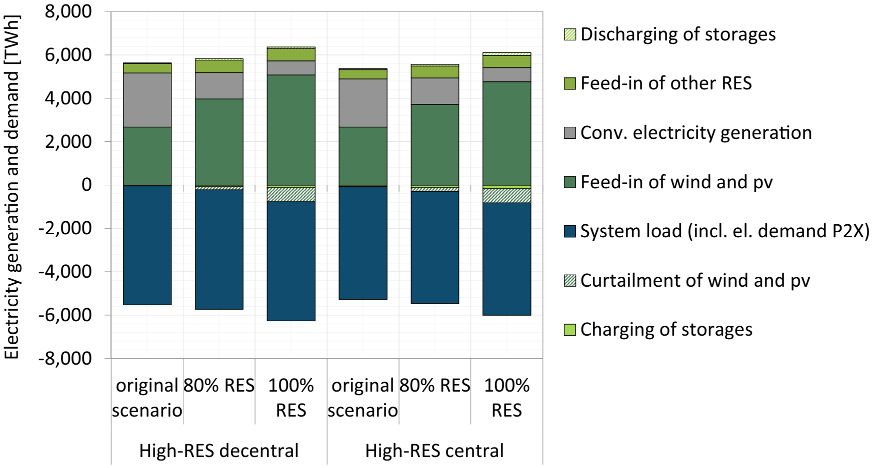

Fig. 10.10 Impact of higher RES share on aggregated electricity generation and demand across all modeled countries in 2050 (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying ELTRAMOD)

10.5 Levelized Costs of Electricity and CO_2 Abatement Costs

Figure 10.11 illustrates the total system cost increase of the electricity system as well as the CO_2 emission reductions from 2014 to 2050 for all scenarios. The system costs include annualized capital costs, fixed and variable operation and maintenance

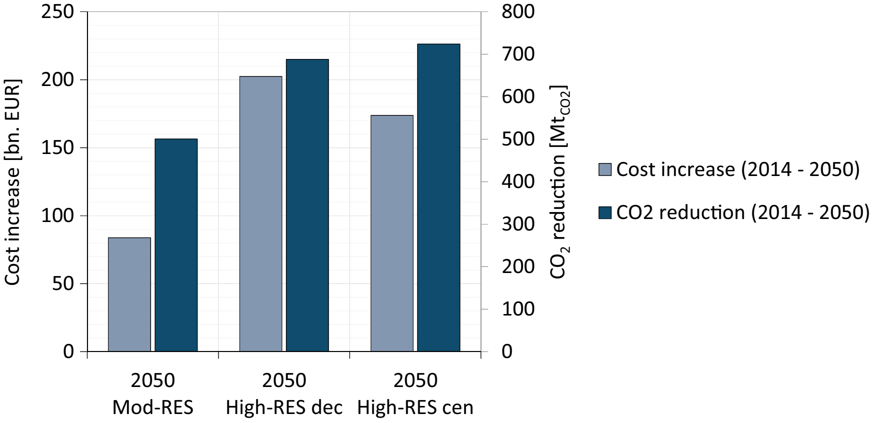

Fig. 10.11 Total yearly system cost increase and CO_2 emission reduction in the electricity sector across all modeled countries in 2050 (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying ELTRAMOD)

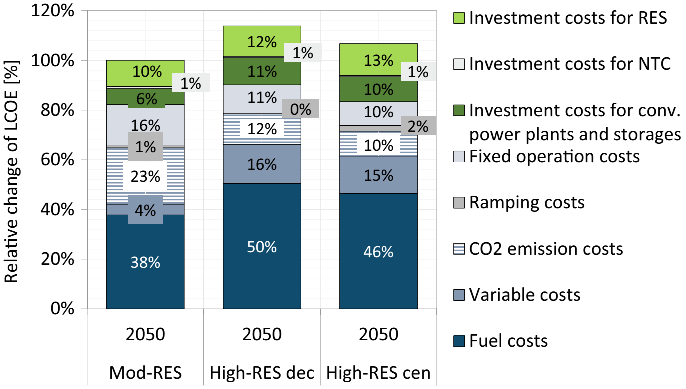

Fig. 10.12 Relative change of levelized costs of electricity (LCOE) for the power sector across all modeled countries in 2050 (EU–27, Norway, Switzerland, United Kingdom, and the Balkan countries) (*Source* Data according to own calculations by applying ELTRAMOD)

costs, fuel as well as CO_2 emission allowance costs. The High-RES centralized scenario shows the highest CO_2 emission reduction and simultaneously a lower cost increase from 2014 to 2050 than the High-RES decentralized scenario. The Mod–RES scenario achieves lower system costs, but realizes less CO_2 emission reduction than both High-RES scenarios (cf. Fig. 10.5).

In this chapter, the levelized costs of electricity (LCOE) are defined as total system costs per unit of electricity generated. Figure 10.12 summarizes the LCOE for all electricity generating technologies, storages as well as the investment costs for net transfer capacities (NTC). To compare the scenarios, the LCOE are normalized to the value of the Mod-RES scenario. Both High-RES scenarios have higher fuel costs compared to the Mod-RES scenario due to the significant increase of electricity demand caused by the enforced sector coupling.

However, due to the dispatch of more low-carbon technologies, such as gas-fired CCS plants, the share of CO_2 emission costs is lower than in the Mod-RES scenario, although the CO_2 price increases significantly from ca. 90 EUR/t_{CO2} in the Mod-RES scenario to approx. 150 EUR/t_{CO2} in the High-RES scenarios in 2050. The High-RES decentralized scenario has the highest LCOE due to more electricity generation to cover higher electricity demand. Hence, the LCOE are +14% and +7% higher in the decentralized and centralized High-RES scenario, respectively, compared to the Mod-RES scenario (cf. Fig. 10.12).

High CO_2 prices and the resulting incentives for optimal investments in low-carbon technologies reduce overall CO_2 emission costs. With the additional electricity demand due to sector coupling in the High-RES scenarios, the overall RES share is similar to the Mod-RES scenario. However, the higher RES capacities required to cover a higher electricity demand only slightly increase the share of RES investment costs, while the costs associated with the fossil-fuel-based back-up capacity (fuel costs, variable costs, and investment costs for conventional power plants) are increasing more significantly in the High-RES scenarios. This further underlines the potential benefit of additional RES capacities regarding the average LCOE.

10.6 Discussion and Conclusion

This chapter analyzes the fundamental changes in the context of a decarbonized electricity sector with cross-sectoral interdependencies between different demand and supply sectors considering the deployment of RES. For the analysis of an optimal flexibility provision in different European least-cost decarbonization pathways, the fundamental electricity market model ELTRAMOD is applied and embedded in the EMS of the REFLEX project. The normative REFLEX scenario framework illustrates the complexity of the future energy system transformation in Europe with possible overlapping development pathways regarding the RES expansion, the level and implementation approaches for sector coupling as well as different levels of flexibility provision.

The results in this chapter highlight the crucial cross-sectoral interactions and their influence on optimal investment and dispatch decisions for different flexibility options from an electricity market perspective. The analysis shows, that the least-cost efficient capacity mix depends on different deployments of DSM appliances. It can be observed that flexible measures in the demand side sectors decrease the value of flexibility options in the electricity market. Since DSM smooths the residual load, electricity market-based storages decrease in value. Nevertheless, an extensive application of DSM, as in the High-RES decentralized scenario, can lead to significant reductions of positive residual load peaks, thus limiting the need for additional (conventional) back-up capacities. These results support the scientific literature (Müller and Möst 2018; Strbac et al. 2012).

Additionally to the interactions with DSM applications, storages are particularly affected by cross-sectoral electrification. Since an electricity demand increase lowers the frequency of low or negative residual loads, incentives for wholesale market-based storage technologies are also reduced. At the same time, sector coupling in combination with less ambitious RES expansion, increases the required conventional power plant capacities. Of high importance regarding the optimal flexibility mix in the power system is also the implementation of power–to–x technologies. A market-based dispatch of investment cost-intensive technologies (e.g., electrolyzers), tends to maximize full load hours of these technologies, and thus rather increase flexibility needs in the electricity sector, mainly provided by additional power plant capacities. In contrast, particularly low capital costs technologies, such as electric boilers and heat pumps in combination with the respective storages, enable a cross-sectoral flexibility provision.

In general, the modeling results indicate, that under the given scenario framework and the input from the model coupling within REFLEX, besides new flexibility options such as DSM and storages, back-up capacities are still necessary to provide system flexibility. The ELTRAMOD results underline the crucial role of high CO_2 prices to achieve the emission reduction targets. Although the High-RES scenarios are characterized by relatively high shares of RES, CO_2 prices higher than 70 EUR/t_{CO2} are required to enforce decarbonization by avoiding investments in carbon-intensive generation technologies in the presence of an increasing electrification of the demand side sectors. High fuel and CO_2 prices can incentivize the competitiveness of low-carbon technologies like gas-fired CCS and flexibility options, such as storages and power-to-x. These results support existing analyses and policy recommendations, e.g., EU Roadmap (European Commission 2011a). The insights gained in this chapter call for the improvement of the EU Emission Trading Scheme (ETS) to enable such high CO_2 prices, to provide more long-term clarity and certainty in price developments as well as to include more CO_2 emitting sectors. Nevertheless, an even more ambitious RES expansion allows for additional significant reductions in fossil fuel-based electricity generation and at the same time increase the value for storage technologies. Only high shares of RES allow for a mix of various flexibility options in the electricity market in a cross-sectoral energy system.

To summarize, the installed flexibility option mix in the electricity market is strongly influenced by the electricity demand and RES feed-in as well as by the sector coupling of the demand side sectors. Differences occur regarding the optimal mix of flexible power plants between the Mod-RES and High-RES scenarios. The combinations of the interactions discussed above result in a rather similar power plant mix in the two High-RES scenarios, although the scenarios are defined by different feed-in characteristics of varying combinations of fluctuating generation from wind and photovoltaic. For the High-RES scenarios, the achievable emission reductions in the present scenario framework and EMS exceed the reduction targets of the European Commission, while the LCOE are increasing rather moderately compared to the Mod-RES scenario. As shown in this analysis, high CO_2 prices, preferably above 70 EUR/t_{CO2}, and high RES shares are a no-regret strategy to achieve the EU emission reduction targets of at least 80–95% in 2050 (compared to the level of 1990).[5] Accordingly, the optimal combination of flexibility options gains in importance in order to facilitate a high integration of intermittent RES.

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[5] The European Green Deal, published after the completion of this project, sets more ambitious targets for reducing CO_2 emissions, and most likely the power sector will also be affected by these ambitious targets in the near future.

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Chapter 11
Impact of Electricity Market Designs on Investments in Flexibility Options

Christoph Fraunholz, Andreas Bublitz, Dogan Keles, and Wolf Fichtner

Abstract Against the background of several European countries implementing capacity remuneration mechanisms (CRM) as an extension to the energy-only market (EOM), this chapter provides a quantitative assessment of the long-term cross-border effects of CRMs in the European electricity system. For this purpose, several scenario analyses are carried out using the electricity market model PowerACE. Three different market design settings are investigated, namely, a European EOM, national CRM policies, and a coordinated CRM. The introduction of CRMs proves to be an effective measure substantially shifting investment incentives toward the countries implementing the mechanisms. However, CRMs increase generation adequacy also in the respective neighboring countries, indicating that free riding occurs. A coordinated approach therefore seems preferable in terms of both lower wholesale electricity prices and generation adequacy.

11.1 The European Debate on Electricity Market Design[1]

Since the liberalization of the electricity markets in the 1990s, the prevailing market design in European countries has been the energy-only market (EOM), in which capacity providers are solely compensated for the amount of electricity they sell on the markets. In this market design, according to theory, scarcity periods lead to peak prices, which enables investors to cover their fixed and capital costs. In other regions of the world, e.g., in several US markets, so-called capacity remuneration mechanisms (CRMs) are a common extension of the EOM with the earliest implementations dating back to the late 1990s (Bublitz et al. 2019). These mechanisms typically aim to reduce the investment risks by offering capacity providers supplementary income on top of the earnings from selling electricity on the spot markets.

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[1] This introductory section was previously published in Fraunholz and Keles (2019).

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The additional generation, storage, or demand side capacity may then in turn help to improve generation adequacy, i.e., avoid shortage situations. Following the classification of the European Commission (2016), six generic types of CRMs can be distinguished:

- *Tender for new capacity*. Financial support is granted to capacity providers in order to establish the required additional capacity. Different variations are possible, e.g., financing the construction of new capacity or long-term power purchase agreements.
- *Strategic reserve*. A certain amount of additional capacity is contracted and held in reserve outside the EOM. The reserve capacity is only operated if specific conditions are met, e.g., a shortage of capacity in the spot market or a price settlement above a certain electricity price.
- *Targeted capacity payment*. A central body sets a fixed price paid only to eligible capacity, e.g., selected technology types or newly built capacity.
- *Central buyer*. The total amount of required capacity is set by a central body and procured through a central bidding process so that the market determines the price.
- *De-central obligation*. An obligation is placed on load-serving entities to individually secure the total capacity they need to meet their consumers' demand. In contrast to the central buyer model, there is no central bidding process. Instead, individual contracts between electricity suppliers and capacity providers are negotiated.
- *Market-wide capacity payment*. Based on estimates of the level of capacity payments needed to bring forward the required capacity, a capacity price is determined centrally, which is then paid to all capacity providers in the market.

In recent years, several European countries seem to face threats in terms of the future generation adequacy and therefore have either already implemented some kind of CRM or are currently in the process of evaluating appropriate solutions (cf. Fig. 11.1). These developments can be attributed to a variety of factors including strongly increasing shares of fluctuating electricity generation from renewable energy sources (RES), decreasing wholesale electricity prices as well as recent phase-out decisions for certain technologies. Yet, the tendency toward applying CRMs to increase investment incentives contradicts the European Commission's preference for an EOM in order to trigger new investments and provide signals for decommissioning in case of overcapacities. Moreover, in a highly interconnected electricity system like the European one, the uncoordinated implementation of local mechanisms might lead to potentially adverse cross-border effects, which stands in strong contrast to the European Commission's goal of creating an internal electricity market in Europe (Bublitz et al. 2019).

This chapter therefore aims to provide a quantitative assessment of the long-term cross-border effects of CRMs in the European electricity system. The electricity market model PowerACE is applied to a region covering Central Western European

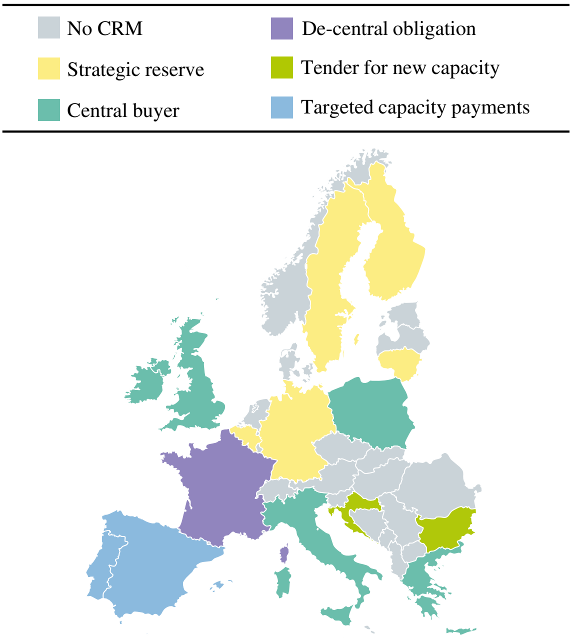

Fig. 11.1 Overview of the future market designs across Europe when all planned CRMs are implemented. Already today, the mechanisms are poorly coordinated, which might intensify due to additional mechanisms being established within the next few years. (*Source* reproduced from Bublitz et al. [2019], classification of mechanisms based on European Commission [2016])

and some Eastern European countries as well as Denmark and Italy. Different long-term simulations up to 2050 are carried out for all three REFLEX scenarios (Mod-RES, High-RES decentralized, High-RES centralized) to derive insights regarding the impact of national and coordinated CRM policies on amount and location of new investments, the resulting technology mixes in the electricity sector as well as generation adequacy.

11.2 Research Design

For the quantitative analyses on electricity market design carried out in the following, the agent-based simulation model PowerACE is applied. A brief overview of PowerACE is given in Chapter 3. Further model details can be found in the following references:

- Coupling and clearing of the day ahead markets (Ringler et al. 2017),
- Generation and storage expansion planning under consideration of cross-border effects (Fraunholz et al. 2019),
- Implemented capacity remuneration mechanisms (Keles et al. 2016).

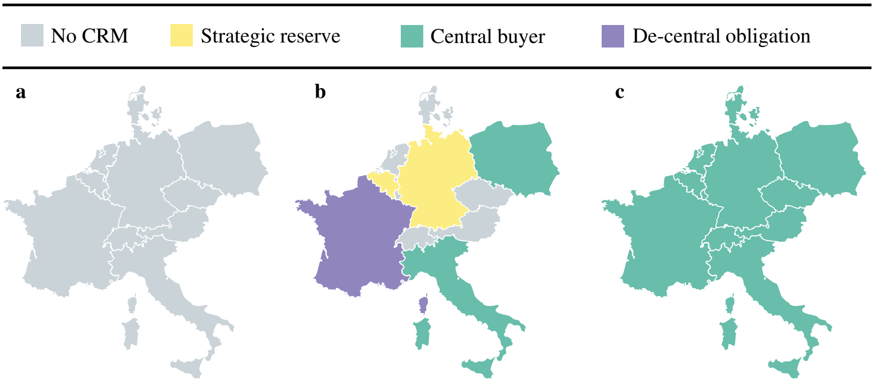

Fig. 11.2 Overview of the market areas modeled in PowerACE and their respective market design in the **a** "European EOM" setting, **b** "National CRM policies" setting, **c** "Coordinated CRM" setting. In order to capture a variety of different design options and corresponding cross-border effects, the regional scope covers Central Western European and some Eastern European countries as well as Denmark and Italy. (*Source* own illustration)

All three REFLEX scenarios (Mod-RES, High-RES decentralized, High-RES centralized)[2] are analyzed considering three different settings with regard to electricity market design (cf. Fig. 11.2):

- European EOM, which serves as a benchmark,
- National CRM policies, in which the market designs of each country as currently implemented or planned are considered,[3]
- Coordinated CRM, which describes a market design potentially standing better in line with the goals of creating an internal electricity market in Europe than unilateral CRMs.

The investment methodology in PowerACE depends on the respective market design. In market areas without an implemented CRM, the investment decisions are solely driven by the future electricity price expectations of the investors. Contrary, in market areas with an active central buyer mechanism, annual descending clock auctions are carried out in order to contract a specific amount of secured generation and storage capacity. For this purpose, the regulator first sets an arbitrary reserve margin, which controls the desired level of generation adequacy and defines the capacity to be procured in the auction.

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[2] Detailed information on the different scenarios are provided in Chapter 2. For recapitulation: (i) the electricity demand grows moderately in Mod-RES and substantially higher in High-RES, (ii) significantly more intermittent renewables are assumed in High-RES than Mod-RES, (iii) decentralized solar power dominates High-RES decentralized, whereas higher shares of offshore wind power characterize High-RES centralized.

[3] Please note, that due to the similarities of the different types of CRMs on an abstract level, the French CRM is modeled using the central buyer implementation in PowerACE, although in reality, a de-central obligation mechanism is used in France.

In case of uncoordinated national CRMs, the reserve margin μ_y^{nat} is set to 1.0, such that the residual load in the respective market area can always be covered by the available conventional generation and storage capacity, without depending on electricity imports. The calculation of the required capacity $c_{m,y}^{\text{nat}}$ is shown in Eq. 11.1, where d denotes the electricity demand, r the renewable feed-in, m the market area, y the year, and h the hour of the year.

$$c_{m,y}^{\text{nat}} = \mu_y^{\text{nat}} \cdot \max_h \left(d_{m,y,h} - r_{m,y,h}\right) \quad \forall m, y \tag{11.1}$$

For the coordinated CRM, the national reserve margin is adjusted by the ratio between peak residual load across all market areas and the sum of the national peak residual loads (cf. Equation 11.2). This procedure is also applied by Bucksteeg et al. (2019). Cross-border synergies obviously lead to lower reserve margins under the coordinated CRM μ_y^{coor} than in the uncoordinated case.

$$\mu_y^{\text{coor}} = \mu_y^{\text{nat}} \cdot \frac{\max_h \sum_m \left(d_{m,y,h} - r_{m,y,h}\right)}{\sum_m \max_h \left(d_{m,y,h} - r_{m,y,h}\right)} \leq \mu_y^{\text{nat}} \quad \forall y \tag{11.2}$$

Contrary to the model-endogenous investment decisions, decommissioning of existing power plants is exogenously defined in PowerACE and based on the respective age and technical lifetime of the generation units, which remain unchanged for all scenarios. Consequently, the development of the future technology mix across the various scenarios strongly depends on the techno-economic characteristics of the different investment options (conventional power plants and storage technologies). Since the expansion of RES is an exogenously defined and scenario-specific input to PowerACE, no additional investments in renewable technologies are considered. Moreover, the learning curves for storage technologies developed within the REFLEX project (cf. Chapter 4) are implemented in PowerACE.

11.3 Development of the Conventional Generation Capacities and Wholesale Electricity Prices

In the following, the simulation results for all three REFLEX scenarios are presented and discussed. The impact of the different market design settings on amount, location, and technology mix of new investments as well as the resulting wholesale electricity price developments is in the focus of the result presentation. The European EOM is used as a benchmark, to which the national CRM policies as well as the coordinated CRM setting are compared.

By imposing a certain capacity target and then offering payments to capacity providers additional to the income from selling electricity on the markets, CRMs tend to shift investment incentives in interconnected electricity markets toward the countries using such mechanisms. In the respective neighboring countries without an own CRM, investment incentives may stay stable, but could as well decrease due to the additional capacity from abroad, which also influences domestic price expectations of potential investors. Consequently, under national CRM policies, both positive and negative cross-border effects may be observed.

Contrary, in the case of a coordinated CRM, capacity targets are set for each country, which may result in stable investment incentives across all interconnected market areas. Moreover, as previously described, the total capacities required to secure generation adequacy are lower in a coordinated CRM, due to cross-border synergies and better balancing of fluctuating electricity production from RES.

With regard to wholesale electricity prices, according to theory, the introduction of CRMs should reduce the amount of scarcity situations and related peak prices and therefore result in lower electricity wholesale prices. However, under national CRM policies, suppressed investments in neighboring countries of those using a CRM may also lead to negative cross-border effects. Consequently, the implementation of a CRM might prove to be less effective as expected when considering only an isolated country.

A coordinated CRM should incentivize sufficient capacity to cover the electricity demand at all times and therefore reduce the wholesale electricity prices in all interconnected market areas. However, these savings come at the price of capacity payments for the additional capacity. These may to a certain extent compensate or even overcompensate the savings achieved by lower wholesale electricity prices. This effect—despite its high practical relevance—is however out of the scope of the work presented in this chapter and should be subject to future research.

Figures 11.3, 11.4, 11.5, 11.6, 11.7 and 11.8 present the development of the total conventional generation and storage capacities as well as resulting wholesale electricity prices for all three REFLEX scenarios and two exemplary countries.[4] Since all of these figures are structured similarly, some general remarks are provided before discussing the obtained results in more detail.

In the top part of the figures, the respective total conventional generation and storage capacities throughout the simulation period of 2020–2050 are shown for each of the three market design settings (European EOM, National CRM policies, Coordinated CRM—from left to right). Furthermore, the respective yearly national peak residual load, excluding imports/exports and storage is depicted as a reference point. As previously mentioned, the capacity developments are based on exogenously predefined decommissioning, which is identical for all investigated settings, as well as on model-endogenous investment decisions for different technologies.

The bottom part of the figures shows the resulting impact on the development of the wholesale electricity prices. For this purpose, the European EOM is defined as a reference and the relative price difference $\Delta p_{m,y}$ is then computed as the mean yearly

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[4] Due to space limitations, only results for France and the Netherlands are presented in this section. These countries are chosen as representative ones in terms of cross-border effects, since France is using a CRM under the national CRM policies, while the Netherlands rely on an EOM, but are surrounded by countries applying some kind of CRM.

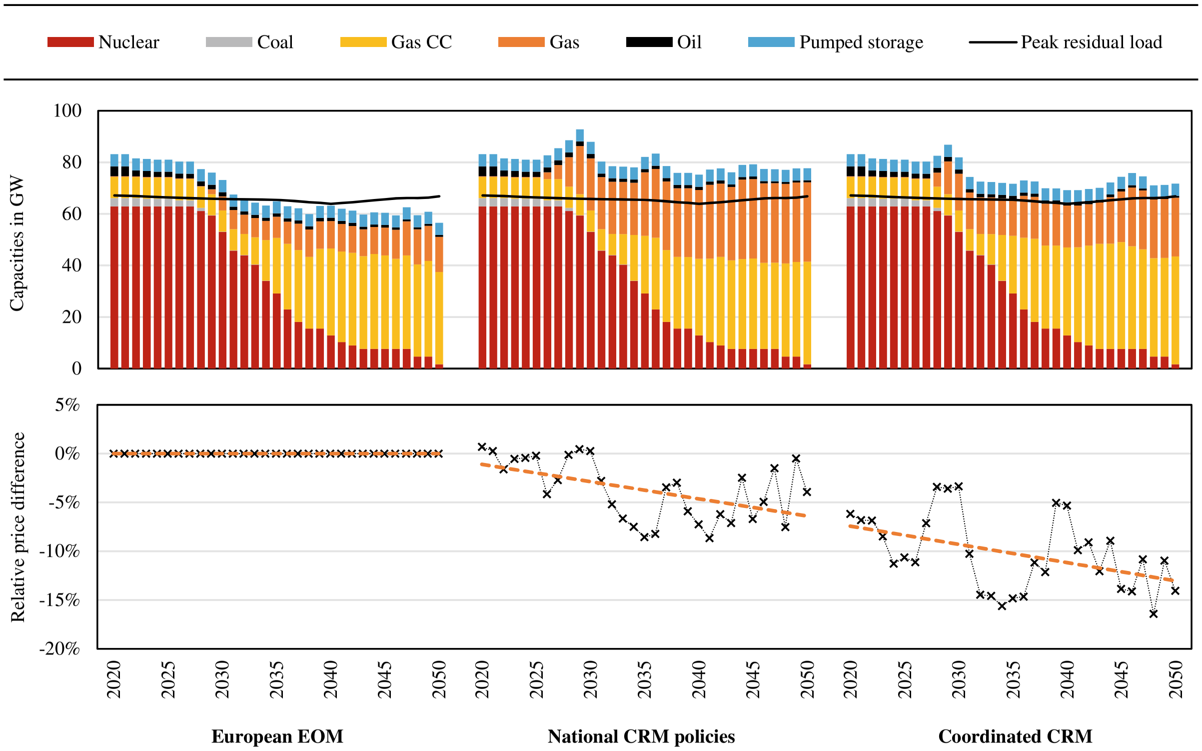

Fig. 11.3 Development of the total generation and storage capacities as well as the resulting wholesale electricity prices (scenario: Mod-RES, country: France). Substantially more investments in OCGTs are carried out under the national CRM policies than in the European EOM and consequently, prices decline. In the coordinated CRM, despite less investments, prices decline even more than under national CRM policies. (*Source* own calculation)

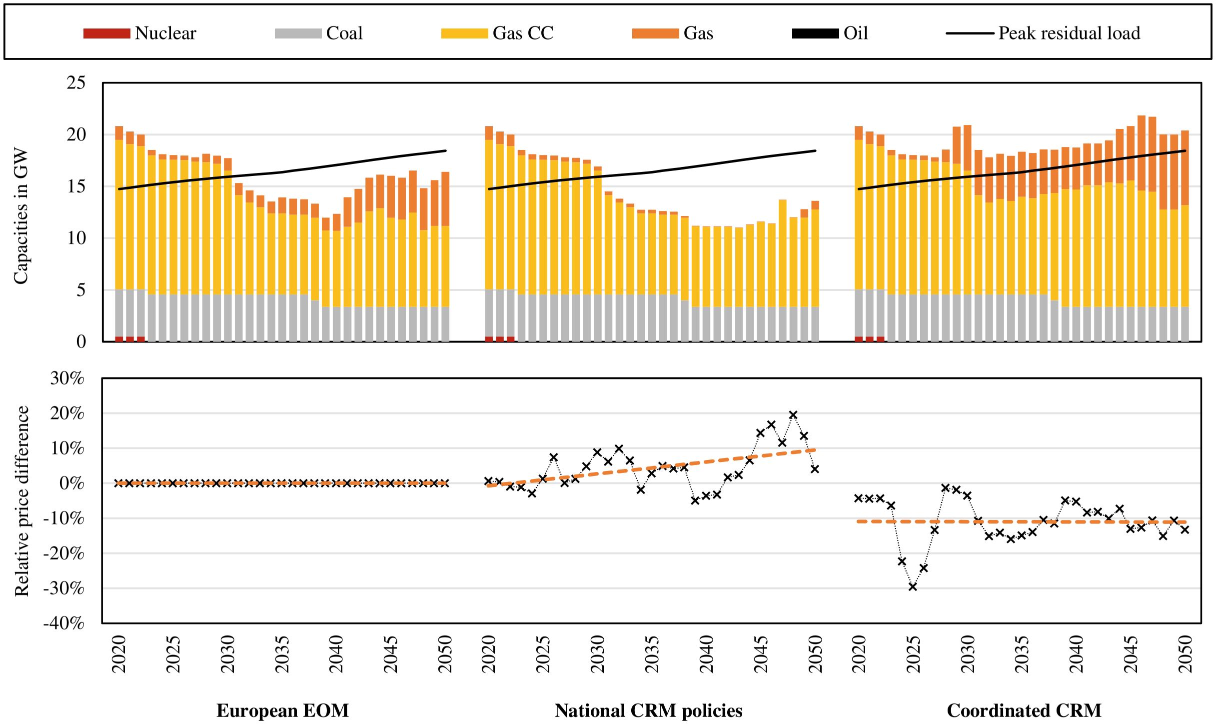

Fig. 11.4 Development of the total generation and storage capacities as well as the resulting wholesale electricity prices (scenario: Mod-RES, country: Netherlands). Investment incentives are drastically reduced under the national CRM policies as compared to the European EOM, leading to substantially less investments in OCGTs and increasing prices. In the coordinated CRM, investment incentives are higher than in both other market design settings, leading to more OCGTs and lower prices. (*Source* own calculation)

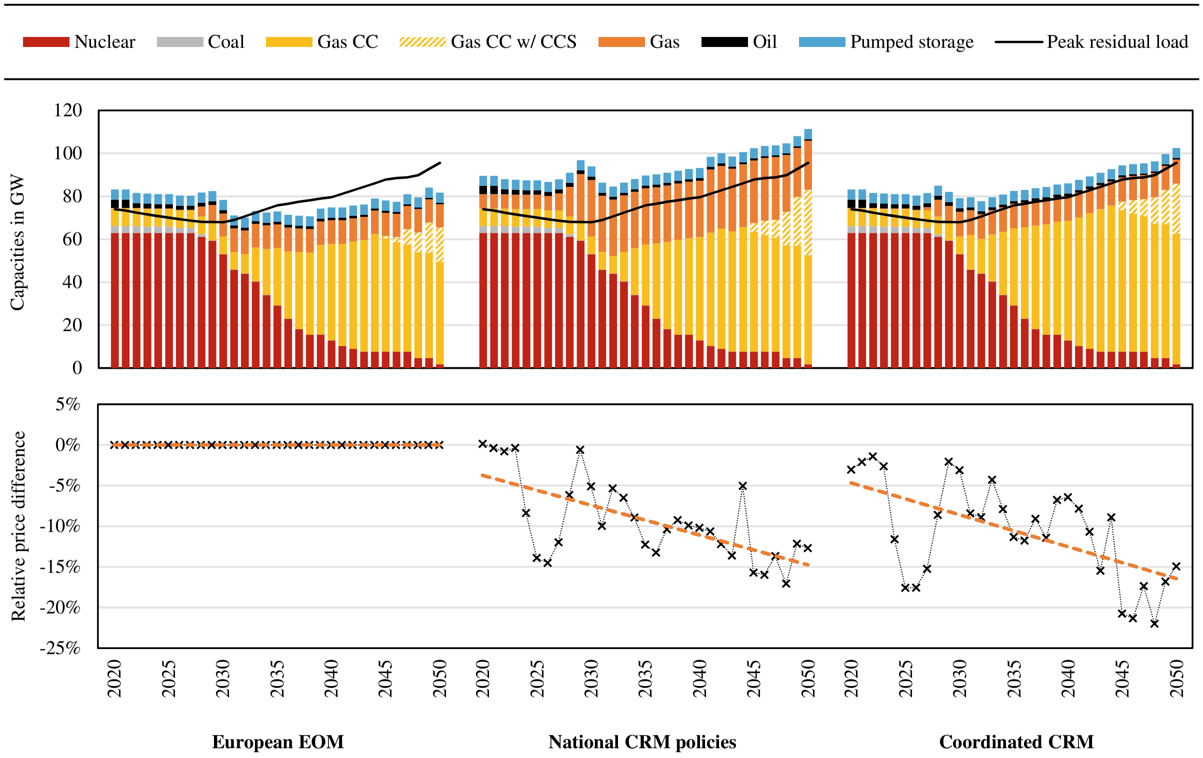

Fig. 11.5 Development of the total generation and storage capacities as well as the resulting wholesale electricity prices (scenario: High-RES decentralized, country: France). Substantially more investments in OCGTs and CCGTs are carried out under the national CRM policies and the coordinated CRM than in the European EOM. Consequently, price decline in these settings. As a result of the high CO_2 prices, some share of gas-fired power plants with CCS technology develops toward 2050. (*Source* own calculation)

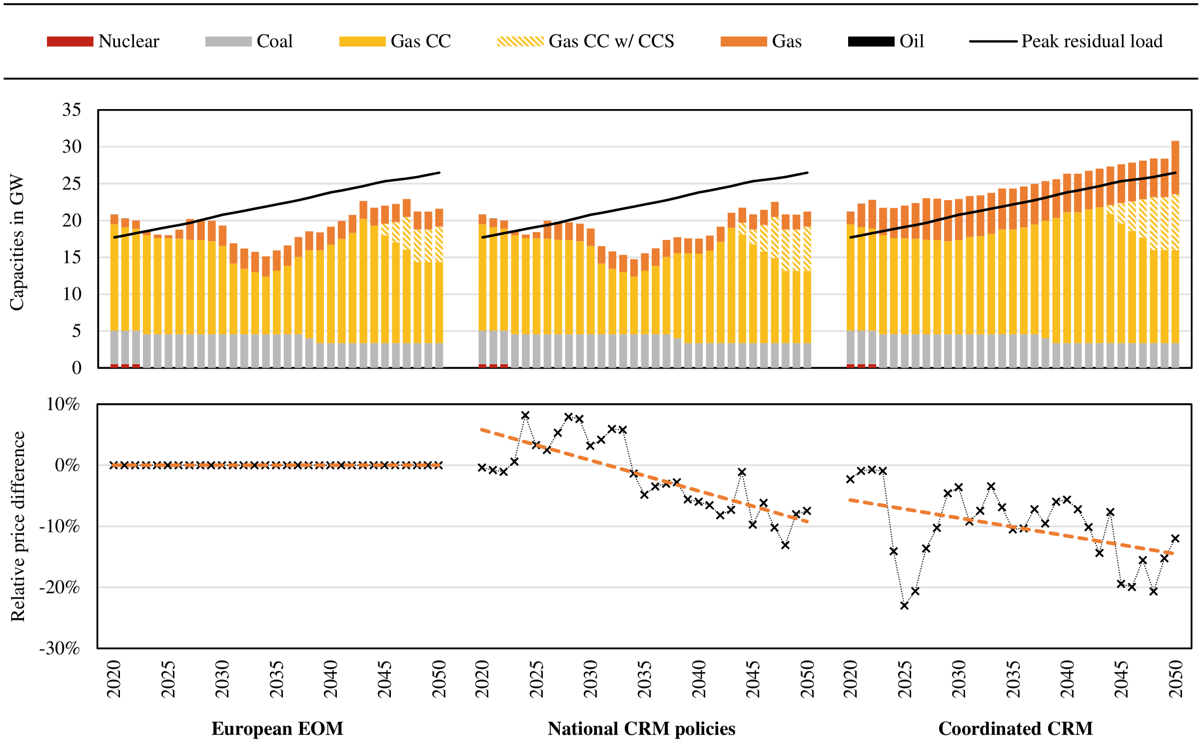

Fig. 11.6 Development of the total generation and storage capacities as well as the resulting wholesale electricity prices (scenario: High-RES decentralized, country: Netherlands). Investment incentives are similar in the European EOM and under the national CRM policies, yet substantially higher in the coordinated CRM. Consequently, more investments in OCGTs and CCGTs are carried out in this setting and prices decline. As a result of the high CO_2 prices, gas-fired power plants with CCS technology become profitable toward 2050. (*Source* own calculation)

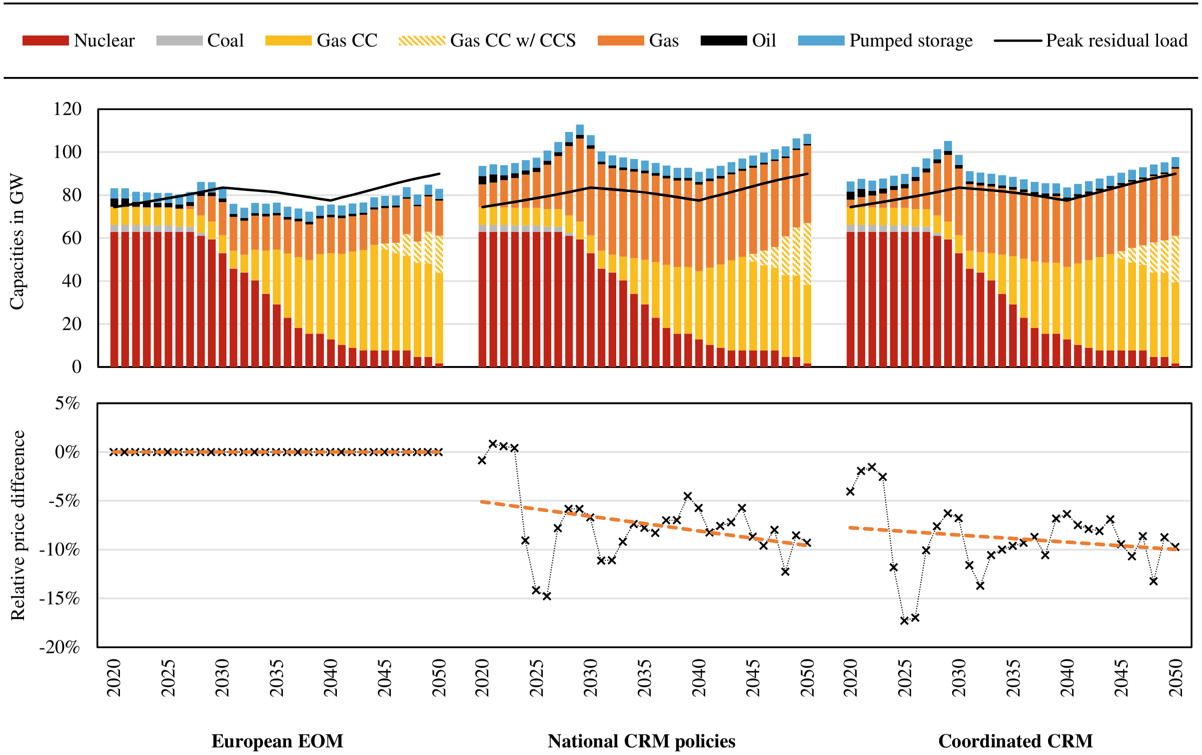

Fig. 11.7 Development of the total generation and storage capacities as well as the resulting wholesale electricity prices (scenario: High-RES centralized, country: France). Substantially more investments in OCGTs are carried out under the national CRM policies and the coordinated CRM than in the European EOM. Consequently, price decline to a similar extent in these settings. Toward 2050, some share of gas-fired power plants with CCS technology develops due to the high CO_2 prices. (*Source* own calculation)

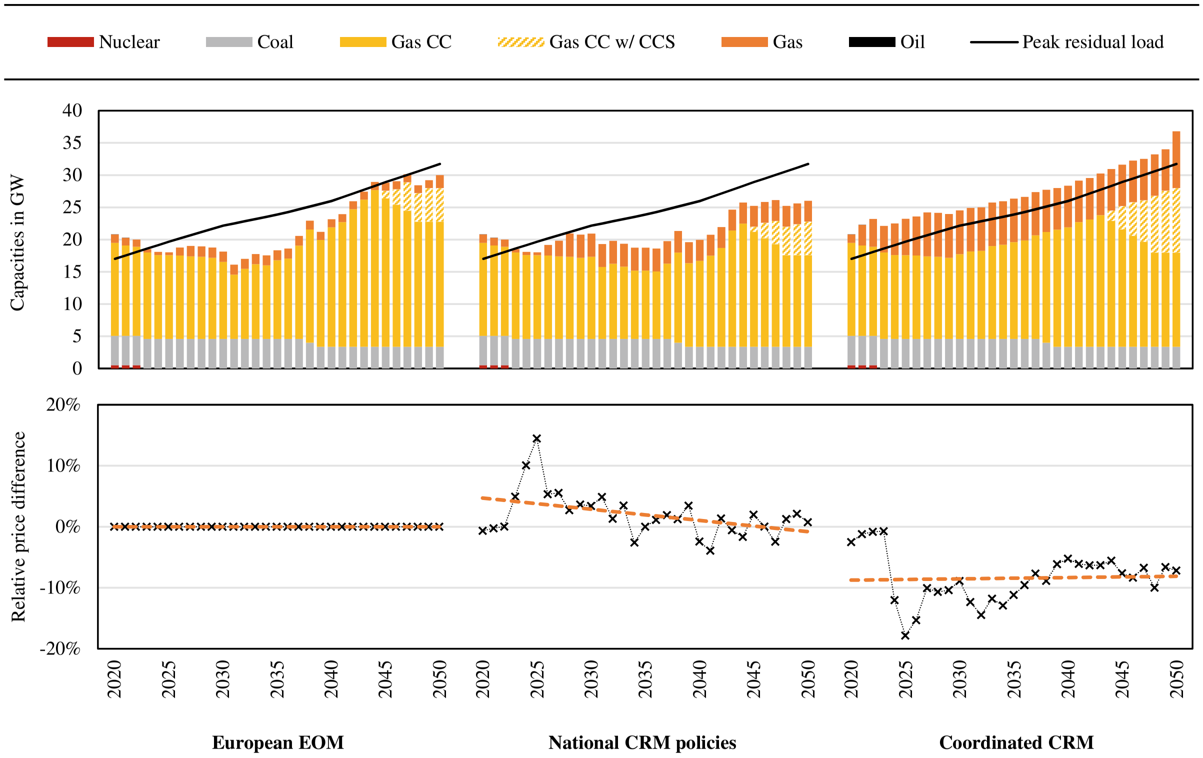

Fig. 11.8 Development of the total generation and storage capacities as well as the resulting wholesale electricity prices (scenario: High-RES centralized, country: Netherlands). Toward the end of the simulation period, fewer investments in CCGTs are carried out under the national CRM policies, while the coordinated CRM incentivizes a substantial amount of additional OCGTs as compared to the European EOM. Prices show an indefinite trend under national CRM policies and decrease under the coordinated CRM. (*Source* own calculation)

price under the respective market design $p^{*}_{m,y}$ divided by that under the European EOM $p^{\mathrm{ref}}_{m,y}$ as shown in Eq. 11.3, where m denotes the market area and y the year. Consequently, by definition, the relative price differences in the European EOM are always at 0% throughout the simulation period. For illustrative purposes, the linear trend of the yearly price differences is also included in the respective diagrams.

$$\Delta p_{m,y} = \overline{p^{*}_{m,y}} / \overline{p^{\mathrm{ref}}_{m,y}} - 1 \quad \forall m, y \tag{11.3}$$

In the following, some specific results of Mod-RES, High-RES decentralized, and High-RES centralized will be presented and discussed.

11.3.1 Mod-RES Scenario

In Mod-RES, some general trends across all modeled countries can be identified:

- A strong fuel switch toward gas-fired technologies, which is mainly driven by increasing CO_2 prices,
- No investments in carbon capture and storage (CCS) technologies, due to an insufficiently high CO_2 price development, which doesn't allow for cost-competitiveness of CCS in view of the higher initial investment and variable costs,
- Low profitability of storage investments, due to the moderate share of electricity generation from RES in Mod-RES. Moreover, the residual load curves provided to PowerACE as exogenous input data are already smoothed by demand side management (DSM) measures (for details cf. Chapters 3, 6, 7 and 8).

As presented in Fig. 11.3, substantially more investments in open cycle gas turbines (OCGT) are carried out in France under the national CRM policies than in the European EOM. This is a direct consequence of the French CRM, which successfully incentivizes additional peak capacity. To a lesser extent, this finding is also true under the coordinated CRM. Since the required reserve margin in a coordinated approach is lower than for a national CRM, less peak load capacity is built in this setting than under the national CRM policies.

The additional capacity has a direct impact on the development of the wholesale electricity prices, which decline under both the national CRM policies and the coordinated CRM as compared to the European EOM. Despite lower capacity levels in France, the price decline is more pronounced under the coordinated CRM. This effect is due to more capacity in the French neighboring countries under the coordinated CRM than under national CRM policies, from which also France seems to benefit.

In the Netherlands, which rely on an EOM, investment incentives are drastically reduced under the national CRM policies as compared to the European EOM. This finding can be attributed to negative cross-border effects caused by the Dutch neighboring countries using CRMs.

Consequently, substantially less investments in peak load capacity, i.e., OCGTs are carried out under the national CRM policies, which results in increasing wholesale electricity prices (cf. Fig. 11.4). Contrary, in the coordinated CRM, investment incentives are higher than in both other market design settings due to a capacity target also for the Netherlands. This leads to additional OCGTs and lower prices.

11.3.2 High-RES Decentralized Scenario

Also in the High-RES decentralized scenario, some general trends across the modeled countries can be identified:

- A strong fuel switch toward gas-fired technologies, similarly as in Mod-RES,[5]
- Substantial investments in CCS technologies toward the end of the simulation period, which is a result of the higher CO_2 prices than in Mod-RES,
- Low profitability of storage investments, for similar reasons as in Mod-RES. Given the strong increase in electricity demand, electricity generation from RES remains moderate in relative terms despite its significant increase in absolute figures. Consequently, investments in OCGTs remain more profitable than storage investments even in the long run. Furthermore, the residual load curves have again been substantially smoothed by DSM measures prior to their use in PowerACE (for details cf. Chapters 3, 6, 7 and 8).

As shown in Fig. 11.5, similarly as in Mod-RES, substantially more investments in OCGTs are carried out in France under the national CRM policies and the coordinated CRM than in the European EOM. However, due to the significant increase in electricity demand and the substantial smoothing of the load curve through DSM measures, the French CRM also incentivizes additional combined cycle gas turbines (CCGT). As a result, the wholesale electricity prices are lower under both the national CRM policies and the coordinated CRM as compared to the European EOM.

Owing to cross-border effects of the CRMs in neighboring countries, the investment incentives in the Netherlands are reduced under the national CRM policies also in High-RES decentralized. Yet, contrary to Mod-RES, these effects are much less pronounced. This is due to the strongly increasing demand across all countries in High-RES decentralized, which leads to a relatively high number of running hours for new capacity and therefore CCGTs often being the more profitable investment option than additional OCGTs. Since CRMs mainly affect the allocation of peak load capacity, i.e., OCGTs, the amount of investments in countries without CRM is less affected by cross-border effects of the national CRM policies in High-RES decentralized than in Mod-RES.

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[5] Although the CO_2 prices are assumed to grow stronger in High-RES decentralized than in Mod-RES, some coal-fired generation remains in the market even in 2050. This is because decommissioning of power plants is only considered exogenously based on their respective age.

In the coordinated CRM, for similar reasons as in France, substantial amounts of additional investments in both OCGTs and CCGTs are carried out. These capacity developments also affect the wholesale electricity prices in the Netherlands (cf. Fig. 11.6). Due to the small reduction in domestic capacities under the national CRM policies and the additional capacity in the neighboring countries, prices decrease even under this setting in the long run as compared to the European EOM. This effect is even more pronounced under the coordinated CRM.

11.3.3 High-RES Centralized Scenario

The general trends regarding fuel switch and profitability of CCS and storage technologies, which could be identified in the results of High-RES decentralized, also apply to the High-RES centralized scenario. Regarding the development of capacity levels and wholesale electricity prices, the patterns in the High-RES centralized scenario are quite similar to those of High-RES decentralized in France. However, due to the significantly lower amount of DSM measures in the High-RES centralized scenario (cf. Chapters 2, 6, 7 and 8), more OCGTs and less CCGTs are built (cf. Fig. 11.7).

In the Netherlands, less CCGTs and more OCGTs are built under the national CRM policies than in the European EOM (cf. Fig. 11.8). This is likely due to a reduced number of running hours for new capacity caused by the additional capacity incentivized in the Dutch neighboring countries due to their CRMs. In the coordinated CRM, the patterns are very similar to those in the High-RES decentralized scenario. Regarding the development of the wholesale electricity prices, no clear trend can be identified under the national CRM policies, while prices decline in the coordinated CRM as compared to the European EOM.

11.4 Impact on Generation Adequacy

Generation adequacy can be defined as the ability of an electricity system to provide sufficient dispatchable generation, storage, and flexible demand side capacity to cover the residual load at any time. Since the electrical grid is not modeled in PowerACE—apart from the simplified consideration of maximum cross-border transmission capacities—grid restrictions are not considered in the evaluation of the generation adequacy presented in the following. Yet, the focus of this work is rather on the ability of different electricity market designs to provide adequate investment incentives to achieve a sufficient capacity level under consideration of the respective cross-border effects.

In order to assess and compare generation adequacy across the various settings and for all modeled countries, a simple, but straightforward indicator is applied. In the investment methodology of PowerACE, no restriction to cover the demand at all times is implemented, but the expansion planning rather emerges from the individual actors' decisions (cf. Chapter 3). Thus, situations may occur in which the day ahead market cannot be cleared due to an insufficient level of dispatchable generation and storage capacity, leading to the maximum day ahead market price of 3,000 EUR/MWh. In reality, reserve capacity would likely be activated, such that even in these scarcity situations, load shedding would not necessarily occur. Yet, the mean number of yearly hours with no successful clearing of the day ahead market in a given market area is a suitable proxy to measure generation adequacy.

Figure 11.9 provides a concise overview of the generation adequacy levels in all scenarios, market design settings, and countries. Across all scenarios, the unilateral implementation of CRMs under the national CRM policies rather obviously increases generation adequacy in the respective countries. However, also neighboring countries of those using a CRM seem to benefit from the additional capacity and face an increase in their generation adequacy levels. This finding indicates that free riding occurs. The effect is most pronounced in High-RES decentralized. As described before, the strongly growing electricity demand in this scenario combined with the extensive use of DSM measures leads to CCGTs often being more profitable than OCGTs. However, since CRMs mainly shift investment incentives for peak load capacity, investments in countries without a CRM barely decline in this scenario. Thus, these countries benefit from an almost unchanged level of domestic capacity plus the additional capacity of their neighbors with CRMs.

Interestingly, generation adequacy increases even further under a coordinated CRM, even in the countries that already use a CRM under the national CRM policies. Apparently, cross-border synergies, better balancing of fluctuating electricity production from RES as well as reduced free riding by neighboring countries without an own CRM, outweighs the impact of lower domestic capacity levels in the respective countries under the coordinated approach.

11.5 Summary and Conclusions

In this chapter, the electricity market model PowerACE was applied to a region covering multiple interconnected European market areas with different electricity market designs. Several long-term simulations up to 2050 were carried out for all three REFLEX scenarios (Mod-RES, High-RES decentralized, High-RES centralized) in order to quantitatively assess the long-term cross-border effects of CRMs in the European electricity system. In this context, three different settings with regard to electricity market design were analyzed. Firstly, a European EOM, which served as a benchmark. Secondly, national CRM policies, including the unilateral introduction of CRMs as currently planned or already implemented in reality. Thirdly, a coordinated CRM as an approach potentially standing better in line with the goals of creating an internal electricity market in Europe than unilateral CRMs. By comparing the different settings, valuable insights regarding the impact of national and coordinated CRMs on amount and location of new investments, the resulting technology mixes

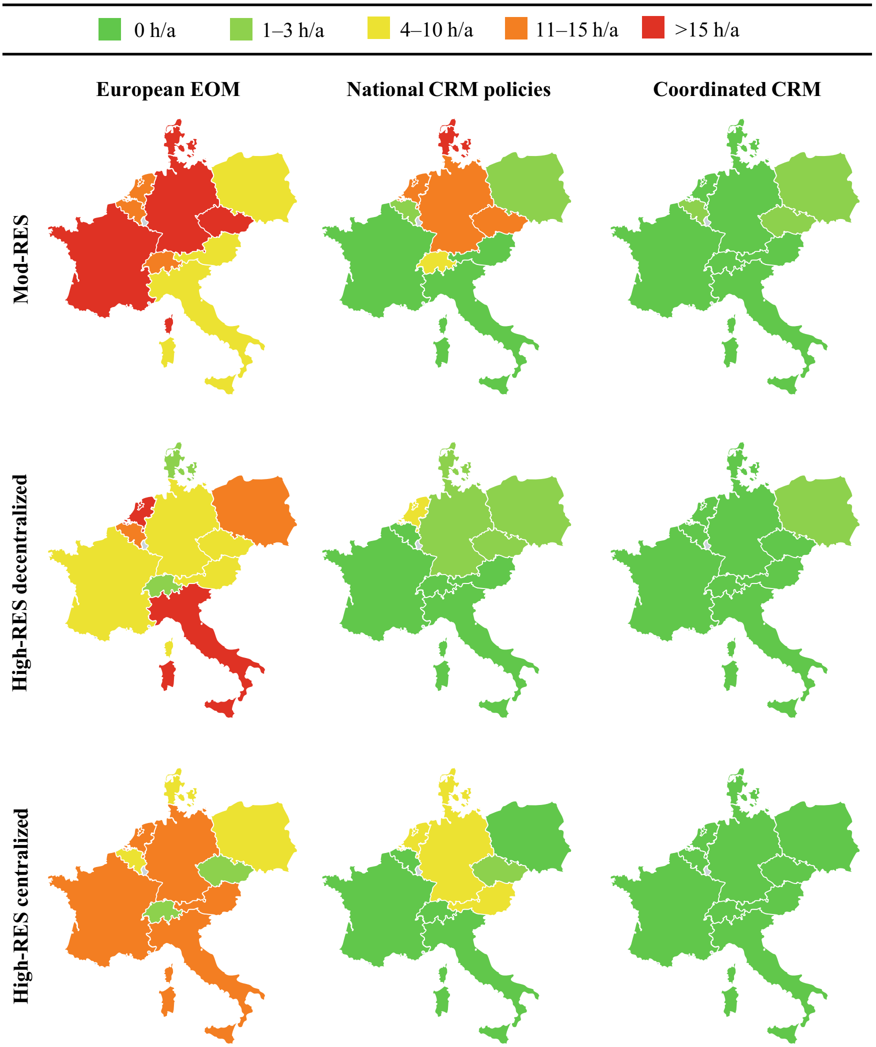

Fig. 11.9 Mean yearly hours with no successful clearing of the day ahead market, i.e., the maximum day ahead market price of 3,000 EUR/MWh due to a shortage of dispatchable generation and storage capacity. All values are averaged over the years 2020 to 2050 and given in h/a. Across all scenarios, the implementation of CRMs does not only increase generation adequacy in the countries using the CRMs, but also in their neighboring countries. (*Source* own calculation)

in the electricity sector, the development of the wholesale electricity prices as well as generation adequacy could be derived.

In terms of the future technology mix, across all investigated scenarios and market areas, a strong fuel switch toward gas-fired power plants can be observed as a result of the assumed CO_2 price development. Due to the more extreme assumptions with regard to CO_2 prices in the High-RES scenarios, CCS technologies turn out to be profitable toward 2050, while this is not the case in the Mod-RES scenario. Furthermore, in all scenarios, storage technologies only play a minor role under the assumptions made. This finding is related to the moderately ambitious shares of renewable electricity generation, even in the High-RES scenarios due to the strongly increasing electricity demand. Besides, the applied electricity load curves are already smoothed by DSM measures prior to their implementation in PowerACE.

The unilateral introduction of CRMs proves to be an effective measure substantially shifting investment incentives toward the countries implementing the mechanisms. The additional generation capacity in these countries in turn reduces both the average wholesale electricity prices and the amount of scarcity situations. Depending on the specific setting, neighboring countries of those implementing a CRM may face both positive and negative cross-border impacts.

In the Mod-RES scenario, which is characterized by a moderate growth of electricity demand, OCGTs often prove to be the most profitable investment option. However, building more peak load capacity in countries with an active CRM drastically reduces investment incentives in neighboring countries without an own CRM, leading to increasing wholesale electricity prices in these countries.

Contrary, in the High-RES scenarios, where the electricity demand grows stronger over time, investments in CCGTs are often economically preferable over peak load capacity. Yet, in contrast to OCGTs, the profitability of CCGTs in countries without an own CRM is less affected by additional investments in neighboring countries with CRMs. Consequently, in the long run, the average wholesale electricity prices may decrease also in countries without an own CRM.

Despite the distortion of investment incentives, across all scenarios, CRMs generally increase generation adequacy not only in the country implementing the mechanism, but also in the neighboring countries, indicating that free riding occurs.

In all three scenarios, a coordinated CRM, in which capacity targets are set for each individual country, provides adequate investment incentives in all countries. Although individual capacity requirements are lower than in case of an unilateral introduction of a CRM, all countries benefit in terms of lower wholesale electricity prices and increased generation adequacy levels. This is also true for countries that already use a CRM under the national CRM policies setting. Apparently, reduced free riding by neighboring countries without an own CRM outweighs the impact of lower domestic capacity levels on wholesale electricity prices in the respective countries under the coordinated approach. However, the savings in terms of wholesale electricity prices come at the price of capacity payments for the additional capacity. These may to a certain extent compensate or even overcompensate the savings achieved by lower wholesale electricity prices. This effect was not considered in this chapter, but should be subject to future research in order to get a holistic picture.

Summing up, whether positive or negative cross-border effects of unilateral CRMs prevail, depends on a variety of factors, including the future development of electricity demand and renewable electricity generation as well as the geographical location of a given country. A coordinated approach generally seems preferable in terms of wholesale electricity prices and generation adequacy. The European Commission should therefore continue to assess potential CRMs carefully prior to allowing their real-world implementation and consider a coordinated European CRM as an alternative market design solution potentially standing better in line with the goals of creating an internal electricity market in Europe.

Although the analyses presented in this chapter provide valuable insights regarding long-term cross-border effects of CRMs in the European electricity system, open questions for future research remain. Two aspects of particular relevance are as follows. Firstly, the role of electricity storage would likely become more visible in a modeling approach where DSM measures simultaneously compete with storage technologies rather than smoothing the electricity load curves prior to their implementation in an electricity market model like PowerACE. DSM measures could then also participate in the CRMs in the same fashion as storage technologies. Secondly, in a real-world setting, also interconnector capacities are typically allowed to participate in CRMs of neighboring countries. Considering this aspect would probably reduce the cross-border effects of unilateral CRMs as presented in this chapter and therefore bring the situation closer to that of a coordinated European CRM, yet at a lower administrative burden.

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Chapter 12
Optimal Energy Portfolios in the Heating Sector and Flexibility Potentials of Combined-Heat-Power Plants and District Heating Systems

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Abstract This chapter examines the role of centralized district heating (DH) systems in context of energy system flexibility and decarbonization. The analysis is performed by applying the model TIMES-Heat-EU. Capacity expansion and operation of the district heating generation units is mainly driven by the evolution of the district heating demand, which varies between the REFLEX scenarios. In all scenarios fuel and technology switches toward bioenergy and natural gas leading to CO_2 emission reduction. Since the total amount of energy produced (both heat and electricity) is the highest in the High-RES centralized scenario, the corresponding CO_2 emissions for district heating are the highest as well. The CO_2 emissions can be reduced by ~60% in 2050 compared to 2015. Furthermore, the role of thermal energy storage and power-to-heat technologies is examined.

12.1 Introduction

At present about half of the final energy consumption in the EU is associated with heating and cooling purposes (European Commission 2016). These energy services are also expected to have a significant share in future energy consumption. In many EU countries, in particular in Scandinavia, Central, and Eastern Europe, a significant proportion of the heat demand in high-density urban areas is covered by district heating networks in which pressurized hot water is used as heat carrier at temperatures below 100°C (Lund et al. 2014). District heating (DH) has the benefits of integrating local heat resources, including waste heat and renewables, and of improved emission control (especially local). Supplying the heat produced in combined heat and power plants (CHPs) not only generates higher overall efficiency but also increases the flexibility of local power systems. Initiatives, such as "District Heat Atlas" (Möller et al. 2018) or "Urban Heat Demand Map" (Wyrwa and Chen 2017) are useful for the

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development of heat supply strategies and plans for different spatial scales such as national, regional, or local. District heating development requires high initial investments, and its economic feasibility is often constrained by the size of the local market. Therefore, various support mechanisms have been implemented by the EU member states to promote district heating and the development of cogeneration, including tax advantages, feed-in-tariffs, certificates, grants, and other kinds of additional support. For instance, Moya (2013) analyzes how to incentivize the growth of CHPs capacities, how to create attractive economic conditions for investors, as well as how to overcome existing barriers, e.g., complexity of the law. Although, there is no clear evidence that the countries which have applied CHP dedicated support mechanisms have been more effective in promoting the development of cogeneration than other countries, the results show that countries where cogeneration plays a significant role are sensitive to the presence of support mechanisms. The analysis carried out in Moya (2013) shows that none of the identified barriers is decisive in preventing the development of cogeneration. The obtained results also indicate that the possible overlap between RES and CHP support programs does not significantly affect the promotion of the CHP development. The report published by Cogen Europe (2011) underlines that the objective of ensuring high efficiency and sustainable development of the European energy system can be achieved through, *inter alia*, the increased use of cogeneration and RES. It is pointed out that the key elements are—firstly, the transition from fossil fuels to RES in electricity and heat production and secondly, the increase in energy efficiency, e.g., through the development of cogeneration. Still in the 2000s district heating has been produced in large extent based on fossil fuels such as gas, coal, or oil. Regardless, the transformation toward a low-carbon (or even carbon-free) district heating systems has already begun and district heating systems are in the focus of a sustainable energy system. Such transformation is possible by enabling a technology switch from fossil fuel to RES (e.g., Sweden is the world bioenergy leader as bioenergy accounts for 33% of the national final energy consumption, cf. World Energy Council (2016)), but also requires further integration of district heating systems into the power system to enlarge district heating flexibility.

Different modeling studies have been performed to analyze potential pathways for future development of the district heating sector. For instance, in Connolly et al. (2014) a methodology based on the combination of geographical information systems (GIS) and the energy system model EnergyPLAN is applied to determine the potential for heat networks and to elaborate plausible district heating development scenarios that would help to further decarbonize the EU energy system. In this chapter the TIMES-Heat-EU model is applied to explore the development of the district heating generation mix for the EU member states in the REFLEX scenarios (cf. Chapter 2).

12.2 TIMES-Heat-EU Model

TIMES-Heat-EU model has been developed to assess the transition pathways toward more sustainable district heating supply and to analyze the role of district heating systems in context of energy system flexibility. The model was formulated with the help of the TIMES generator (Loulou 2008) and belongs to the class of integrated capacity expansion and dispatch planning models. TIMES-Heat-EU is dedicated to model the centralized heat supply by heat-only plants (HOPs) as well as combined heat and power plants (CHPs). The district heating demand is divided into three end-use sectors: the residential, tertiary, and industry sector.

The model uses a bottom-up approach, in which CHPs and HOPs are aggregated into main types according to the fuel used and type of installed turbine (cf. Fig. 12.1). The model considers main types of thermal energy storage (TES) in a short-term and seasonal perspective. The application of thermal energy storage enables the decoupling from power generation and heat generation. The operation of CHPs is influenced by electricity price signals. Power-to-heat (PtH) technologies, such as large electric heaters and heat pumps, can use electricity that would be otherwise curtailed (e.g., RES surpluses). The geographical coverage of the model considers the member states of the EU-27 and the United Kingdom. The time horizon covers the time period from 2015 to 2050 with five years' time steps. Each modeling year is further divided into 224 time-slices derived by aggregating the data every three hours in seven days for four seasons (8 x 7 x 4). The model is calibrated for 2015 based on the EUROSTAT data (Eurostat 2017a; Eurostat 2017b; Eurostat 2017c).

TIMES-Heat-EU solves the linear programming problem of district heating supply. District heat producers, represented by heat-only-plants, CHPs, and PtH, are maximizing their surplus. The optimization is constrained by a set of equation and inequalities. The main equations include: (i) commodity balance equations e.g., for district heating and electricity, (ii) CHP annual overall efficiency requirements

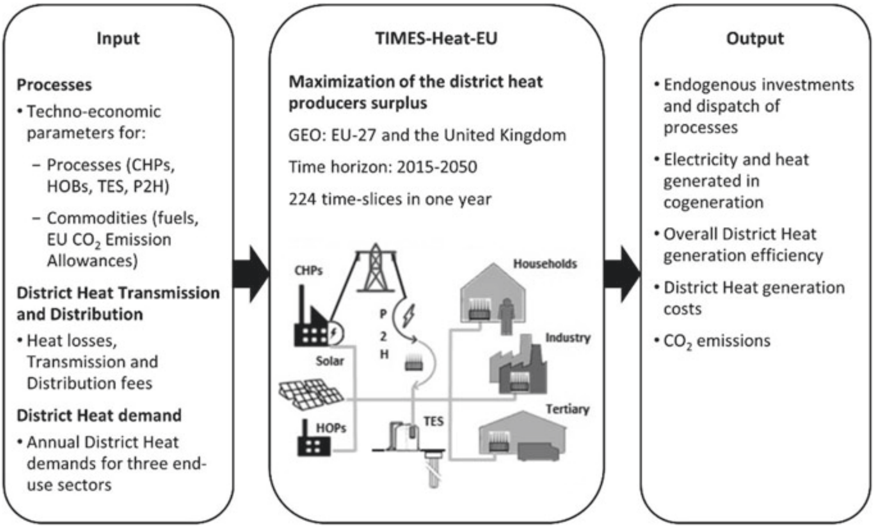

Fig. 12.1 Schematic illustration of the district heating supply model—TIMES-Heat-EU (*Source* Own illustration)

in compliance with the EU legislation, (iii) required share of electricity generated in highly efficient cogeneration, (iv) ramping constraints for the operation of units.

The main output is the mix of heat generating technologies and their dispatch as well as the district heating prices. For a given country the district heating price is calculated as the weighted average (by heat production level) of district heating generation costs of individual CHPs and heat-only-plants including costs of purchasing CO_2 allowances under consideration of the EU ETS. The results of TIMES-Heat-EU underline the economic feasibility of more flexible and RES-oriented cogeneration.

12.3 Developments in the District Heating Sector

One of the most important input parameters influencing the development of district heating systems is the change in the future district heating demand, which is exogenous input parameter for TIMES-Heat-EU provided by the FORECAST model (cf. Chapters 3, Chapter 6 and 7).

As illustrated in Fig. 12.2, the demand for district heating in 2050 is expected to be lower than today in the Mod-RES and High-RES decentralized scenario, mainly due to progressive implementation of low-energy and refurbished buildings. The more significant drop in the High-RES decentralized scenario is due to the fact that, on top of that, central heating systems play a more important role in this scenario. Only the High-RES centralized scenario assumes an increase in the future DH demand mainly because of supporting measures introduced in this scenario in the FORECAST model, such as reinforcing district heating network to realize a more viable heating infrastructure (cf. Chapter 6).

The additional constraint considered in TIMES-Heat-EU is that in the Mod-RES and High-RES centralized scenarios the overall EU-wide relative share of electricity

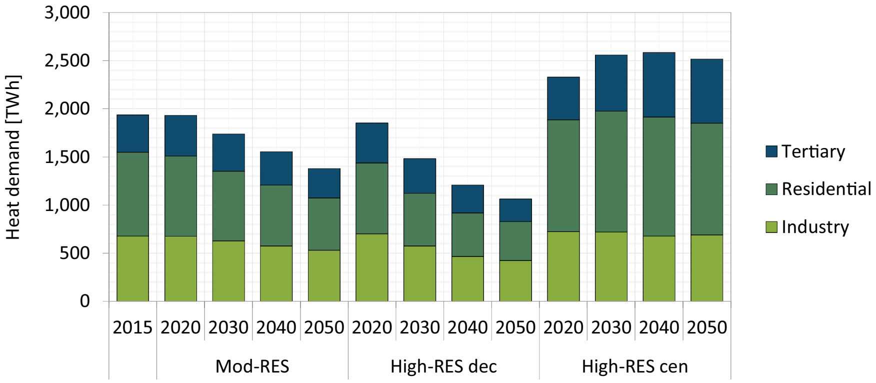

Fig. 12.2 Development of district heating demand in REFLEX scenarios across all modeled countries (*Source* Data according to model results from FORECAST)

produced in cogeneration will be the same as today, i.e., approximately 12%. This assumption is in line with the results of the EU28 Reference Scenario 2016 (cf Capros et al. 2016) derived by applying the PRIMES model. Such constraint is not imposed in the High-RES decentralized scenario due to infeasibility of the solution.[1]

Others factors influencing the model results are: prices of CO_2 emission allowances, techno-economic parameters of processes employed in DH systems as well as potentials and costs of fuel and energy carriers. The coupling of the power and heat sectors is introduced by enabling CHPs having income from both, heat as well as electricity sales. At the same time, the application of power-to-heat technologies requires on the one hand, purchased electricity from the market and, on the other, generates income from heat sales. The income from heat sales is based on the average annual DH price calculated by TIMES-Heat-EU, whereas the income from electricity sales is based on the wholesale electricity prices calculated by ELTRAMOD (cf. Chapters 3 and 10). Thus, the price signals on the wholesale market derived in an iterative model coupling process with ELTRAMOD play a crucial role not only for dispatch decisions regarding CHPs, heat storage systems, and power-to-heat technologies, but also for investment decisions regarding new generation capacities. Moreover, the obtained results consider competition between existing actors (DH generation technologies), which is not always straightforward. For instance, reacting to the low electricity prices during some periods (time-slices), power-to-heat technologies have an incentive to produce district heating and thus rise the residual load contributing to upward flexibility (i.e., increasing electricity demand). However, with limited overall district heating demand, this heat could not be any longer produced in CHPs and thus is a lost opportunity to gain income from district heating and electricity sales. It has also consequences on the general activity of CHPs due to the efficiency requirements imposed on electricity from CHPs. As stated by the Directive 2012/27/EU electricity is considered as produced in high efficiency cogeneration only if the total annual efficiency of the unit is greater than 75 or 80% (depending on the technology employed).

12.3.1 Scenario Results

Figure 12.3 depicts the development of electricity generating capacities of CHPs in the different REFLEX scenarios. In general, a switch toward natural gas and bioenergy-fueled plants can be observed. In the Mod-RES scenario some coal-fired capacities exist, but these are plants that are decommissioned and thus ending their operation in 2045 (cf. fuel input in Fig. 12.8).

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[1] TIMES-Heat-EU contains a constraint to enforce new CHP plants to work as high-efficiency cogeneration units. This means that the ratio of energy output (heat and electricity) to fuel input has to be greater than the given efficiency threshold (e.g., 80% for CCGT). This efficiency requirement cannot be achieved with low DH demand while enforcing CHP plants to have a 12% share in total electricity generation—as it is in High-RES decentralized scenario (cf. Fig. 12.2). The actual shares of electricity generated by CHP units for each scenario are given in Table 12.1.

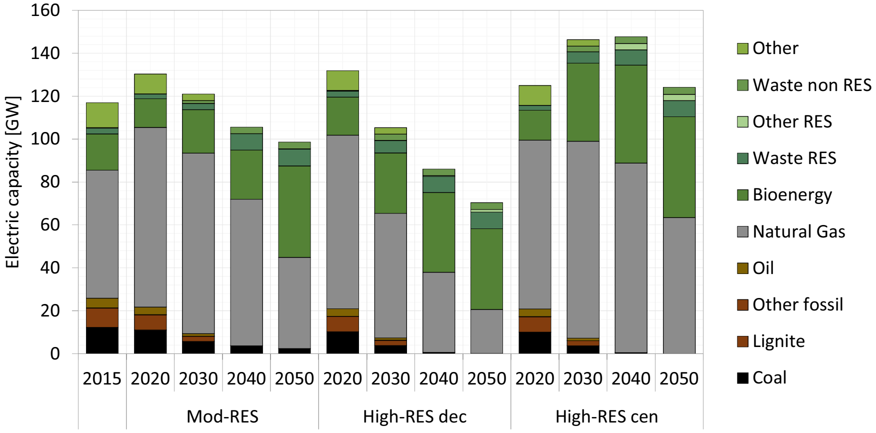

Fig. 12.3 Overall electric capacity of CHP plants in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

In the case of the High-RES scenarios, due to increasing CO_2 prices no other fossil fuels than natural gas-fired power plants are installed from 2030 onwards. The capacity expansion of CHPs is mainly driven by the evolution of the district heating demand. That is why the highest capacity expansion can be observed in the High-RES centralized scenario. In the decentralized case, electricity is generated to a lesser extent in cogeneration.

In the case of heat-only plants (HOPs) the existing thermal capacities are decommissioned until 2030. In general, heat-only-plants are losing competition with CHPs as they can profit only from heat sales, whereas plants operating in high efficient cogeneration can generate profit from both: electricity and heat sales. New capacity installations of heat-only technologies consist mainly of large solar thermal plants, this is especially true for the centralized High-RES scenario (cf. Fig. 12.4).

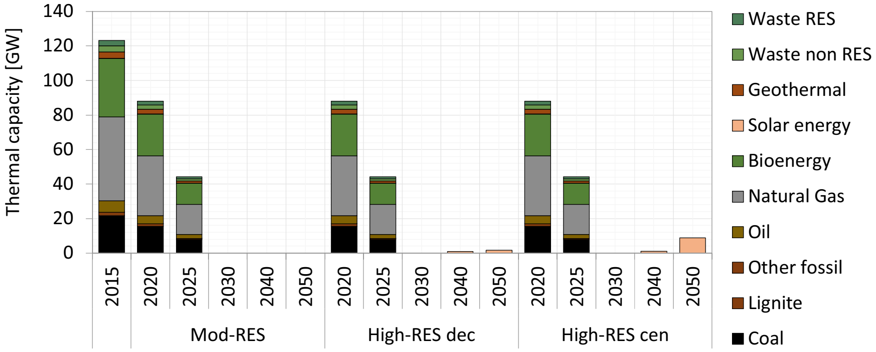

Fig. 12.4 Overall thermal capacity of heat-only plants (HOPs) in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

PtH technologies in TIMES-Heat-EU include electric boilers and large-scale heat pumps. Their operational pattern is different. Both PtH types are consuming electricity purchased on the wholesale electricity market. Heat pumps are assumed to operate constantly within seasons and do not actively react to the changes of the electricity price. They are more capital intensive but have higher efficiencies (the minimum value of COP is set to 3). In contrary, electric heaters serve as peak load units that actively respond to electricity price variations by generating heat that can be stored.

Figure 12.5 presents the installed thermal capacities of PtH. The greatest capacity expansion, mainly electric heaters, can be observed in the High-RES centralized scenario, in which electricity price variations are higher compared to the other scenarios (there are many time-slices with low electricity price). In the centralized scenario lower incentives for DSM actions are assumed in the eLOAD model (cf. Chapters 6 and 7), that is used to generate hourly electricity demand profiles (cf. Chapter 3).

The TIMES-Heat-EU results for power-to-heat have to be interpreted differently than those of ELTRAMOD as both models represent different PtH modeling approaches: TIMES-Heat-EU is focused on the district heating sector and large-scale PtH technologies. ELTRAMOD focuses more on small scale PtH technologies in residential and tertiary individual heating systems.

In TIMES-Heat-EU, thermal energy storages (TES) allow for short-term and seasonal storage, helping to balance heat demand and supply. Each scenario assumes the same relative split of annual district heating demand into individual time-slices (based on the outdoor temperature data). However, in absolute values, the district heating demand differs in time-slices due to the differences in annual district heating demands (which is the highest in High-RES centralized and the lowest in the decentralized scenario). It can be distinguished between three kinds of thermal energy storage systems, i.e., sensible thermal energy storage (STES), latent heat storage by phase-changing materials (PCM), and thermal-chemical storage (TCS). TIMES-Heat-EU considers only sensible thermal energy storage, as phase-changing materials and thermal-chemical storage are still at a research and development stage and

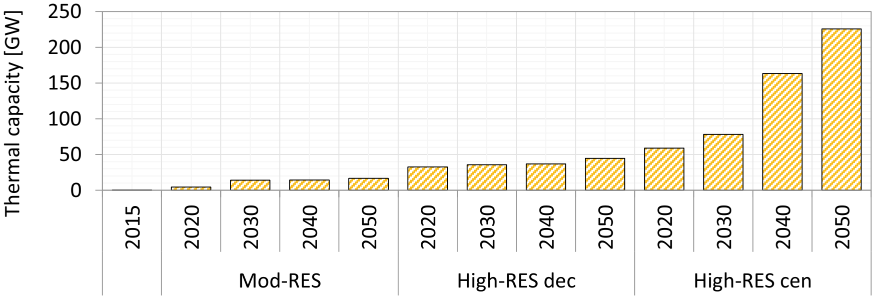

Fig. 12.5 Overall heat generation capacity of power-to-heat technologies in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

therefore require high investments (the advantage lies in higher storage capacity). More specifically, water tanks are selected for short-term storages, whereas borehole thermal energy storages are assumed for the seasonal storages. Figure 12.6 presents the overall amount of heat that flows out of thermal energy storages in the different REFLEX scenarios. The highest flows from inter-seasonal storages can be observed in the High-RES centralized scenario because district heating demand varies most (in absolute values) between seasons in this scenario. Short-term storages depend on the variations of DH demand between time-slices as well as on the changes in electricity prices, which influence the operation of PtH technologies.

Seasonal storages are employed mainly by large solar thermal plants and electric heaters. In some time-slices, in particular during summer time, RES electricity is still curtailed to some extent. This curtailed electricity could have been used by PtH technologies and stored in thermal energy storages, if sufficient capacities of PtH and TES had been available. However, decisions in terms of investments into new capacities are results of the economic optimization. Results show that only limited, economically viable investment in TES and PtH are made for which the costs are outweighed with the profits from the sales of district heat at a later date.

TIMES-Heat-EU calculates the weighted average annual district heating generation costs (WA-DH generation costs). In a first step, the unit district heating generation costs are calculated for each heat generation technology. These costs include fuel, fix and variable operation and maintenance costs, annualized investments as well as costs of CO_2 emission allowances. In a second step, the total costs are divided by the amount of heat produced to calculate unit costs of heat generation by the given technology. This calculation is straightforward in case of heat-only-plants. In case of CHPs, the total costs are split into two parts and assigned to power and heat generated. Finally, the unit generation costs are weighed by heat production to deliver weighted average annual district heating generation costs. The development of district heating costs for selected countries (with the highest DH demand) and EU-27 + UK average is presented in Fig. 12.7. The average district heating generation costs are, in general,

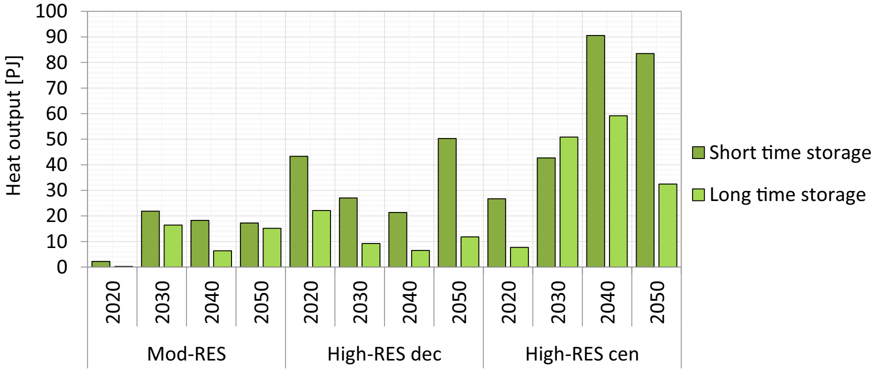

Fig. 12.6 Heat flow out of thermal energy storage in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

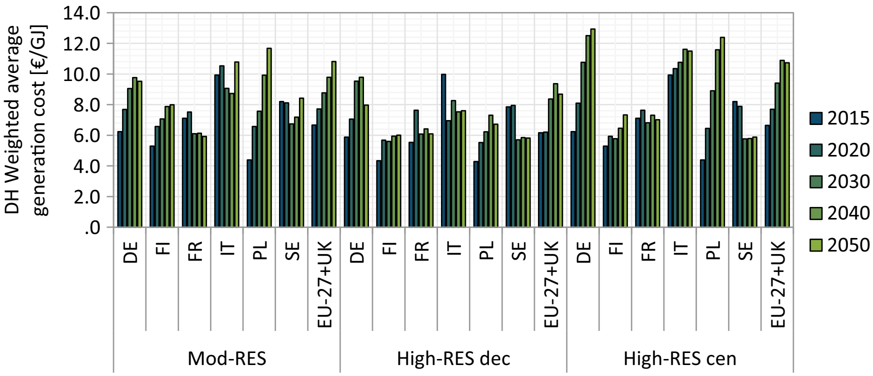

Fig. 12.7 Average district heating generation costs in the REFLEX scenarios for selected countries (*Source* Data according to TIMES-Heat-EU model results)

lower than the reported overall district heating price for the end-users (usually local DH operators are adding distribution and other fees, cf. Euroheat and Power 2017).

The weighted average annual district heating generation costs are increasing compared to the base-year in most of the EU-27 member states and the United Kingdom. This is mainly due to: (i) investments in new capacities, (ii) rising prices of CO_2 emission allowances, and (iii) higher operational costs. Regarding (i), it should be mentioned, that investments for units that already exist in 2015 are considered in TIMES-Heat-EU as sunk costs. In the future the existing heat-only plants are replaced with CHP plants. This also has an impact as CHPs total costs are only partly assigned to heat. In reference to (ii), the weighted average annual district heating generation costs depend on the carbon intensity of the district heating generation mix. This in turn, depends on the potentials of the renewable resources and their exploitation. For instance, in the High-RES centralized scenario the bioenergy potential is fully exploited due to high district heat demand and therefore more gas-fired units have to be utilized, what is not the case in High-RES decentralized scenario. Finally, with regard to (iii), also the operational costs including mainly fuel costs have an impact on WA-DH generation costs.

As presented in Fig. 12.8, in all scenarios there are fuel and technology switches toward bioenergy (mainly biomass) and natural gas as well as toward heat production in cogeneration. Clearly, bioenergy-based CHP units are replacing existing solid fuel-fired heat-only-plants and CHPs. Natural gas units are utilized in countries with low bioenergy potentials.

Figure 12.9 presents the amount of electricity produced in cogeneration for the REFLEX scenarios. As mentioned before, in case of the Mod-RES and High-RES centralized scenario the constraint to maintain about 12% of the total electricity production by CHP plants is assumed, which is not the case in the High-RES decentralized scenario. Thus, the highest electricity production occurs in the High-RES centralized scenario. In the High-RES decentralized case, the amount of electricity

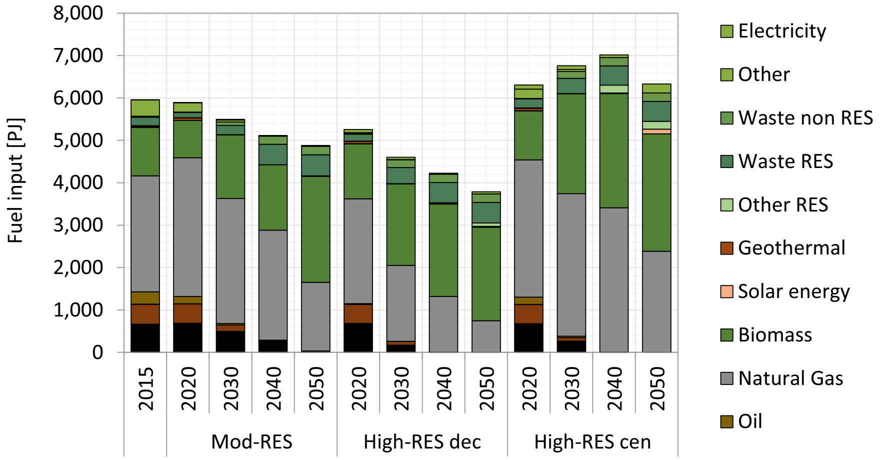

Fig. 12.8 Fuel input for DH generation in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

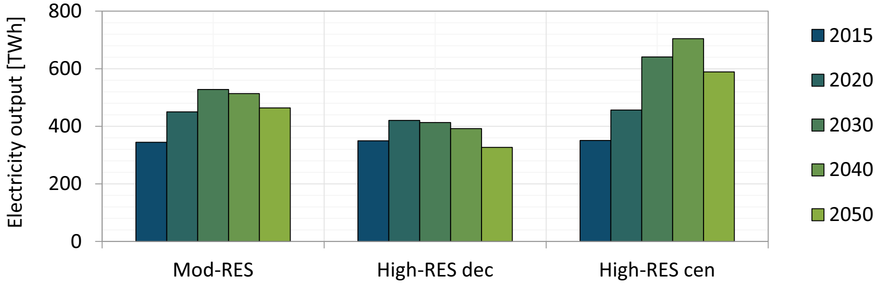

Fig. 12.9 Electricity generation of CHPs in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

produced is associated with the DH demand and is limited by the annual efficiency requirement of cogeneration units.

12.3.2 CO_2 Emissions in the Heating Sector

The switch in the district heating generation mix toward renewables and cogeneration results in decreasing CO_2 emissions in all scenarios as depicted in Fig. 12.10.

Since the total amount of energy produced (both heat and electricity) is the highest in the High-RES centralized scenario, the corresponding CO_2 emissions are also the highest in this scenario. However, as compared to the Mod-RES scenario with much lower energy (district heating and electricity) demand, the CO_2 emission factor per

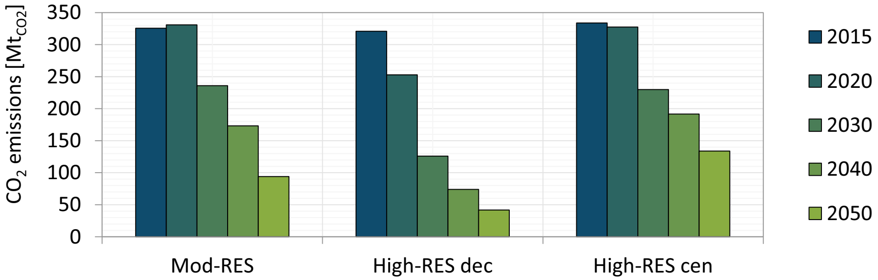

Fig. 12.10 CO_2 emissions from district heating generation in the REFLEX scenarios across all modeled countries (*Source* Data according to TIMES-Heat-EU model results)

total energy output in 2050 in the High-RES centralized scenario is only slightly higher, as presented in Table 12.1. The reason for this is that in High-RES centralized scenario all CO_2 neutral fuels (e.g., bioenergy) are used up to their supply limits, what implies the necessity to use some fossil fuels. This explains why in the High-RES decentralized scenario this emission factor is the lowest (cf. fuel input structure in Fig. 12.8). Table 12.1 summarizes the results of TIMES–Heat–EU. Specific CO_2 emissions in the Mod-RES scenario are higher than in High-RES decentralized because more natural gas is used in this scenario, i.e., 33 and 20%, respectively. Both scenarios have similar district heating demands, but more electricity needs to be generated in the Mod-RES scenario, due to the constraint enforcing a 12% share of CHP plants in electricity generation.

12.3.3 Sensitivity Analysis

One of the most important parameters influencing the results is the bioenergy supply (biomass and biogas). The available bioenergy potential has been estimated based on (Elbersen et al. 2012; Ruiz et al. 2015) and it was assumed to be 10% higher in 2050 as compared to 2015. Bioenergy consumption increases in every scenario, reaching the limit (available potential) in the High-RES centralized scenario. A sensitivity analysis was carried out, in which the bioenergy potential in 2050 was modified in a range from −100% to +80%. Therefore, in 2050, according to the former the bioenergy potential was equal to zero, while for the latter it was increased by 80% (which in absolute terms gave a number about four times higher than total bioenergy consumption in 2015). Potentials available in intermediate years were interpolated linearly between 2015 and 2050.

The following discussion on the impact of bioenergy does not consider results of the Mod-RES scenario, as the High-RES decentralized and centralized scenario represent two extreme cases in terms of electricity and district heating demand. Figure 12.11 presents renewable energy share (mainly bioenergy but also other RES) in primary energy consumption in the DH generation sector as function of bioenergy

Table 12.1 Summary of the key results of the TIMES-Heat-EU model

Scenario	Mod-RES			High-RES dec			High-RES cen		
Year	2015	2030	2050	2015	2030	2050	2015	2030	2050
Electricity generation [TWh]	344	528	464	350	413	327	351	641	589
DH generation [PJ]	3.291	2.893	2.541	3.144	2.627	2.230	3.360	3.669	3.641
Fuel input [PJ]	5.957	5.495	4.881	5.840	4.601	3.787	6.097	6.761	6.331
Renewable energy share [%]	23	31	62	23	52	75	23	40	51
CO_2 emissions [Mt_{CO2}]	326	236	94	321	126	42	334	230	134
Total system efficiency [%][a]	76	87	86	75	89	90	76	88	91
CO_2 emission per total energy output [kt_{CO2}/PJ]	**72**	**49**	**22**	**73**	**31**	**12**	**72**	**38**	**23**
Share of CHP in total electricity generation [%]	12	18	15	12	13	7	12	20	15

[a] calculated as a ratio between total electricity and heat output (including PtH) to fuel input

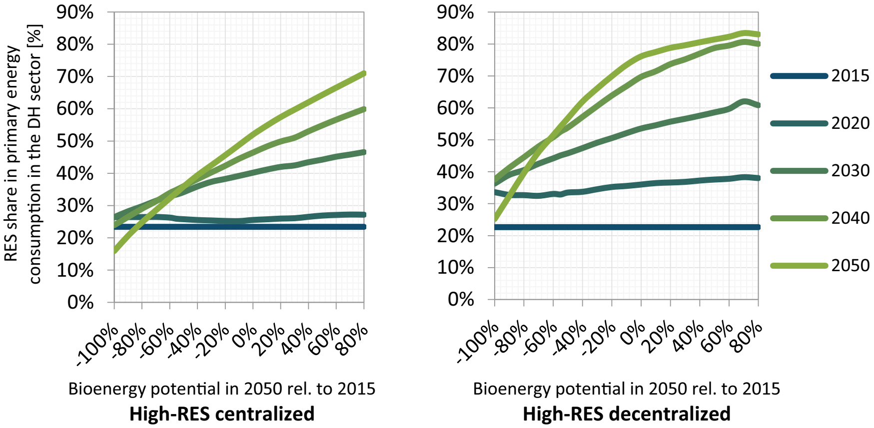

Fig. 12.11 Share of renewable energy in primary energy consumption in the district heating generation sector as function of bioenergy potentials in the High-RES centralized (left) and High-RES decentralized scenario (right) (*Source* Data according to own calculations)

potentials. Note, that in the future years it would be much easier to achieve greater RES shares in the primary energy consumption (PEC) in the High-RES decentralized scenario. This is because the overall PEC is much lower in the district heat sector in this scenario due to lower DH demand (cf. Fig. 12.2). In both scenarios the increase of bioenergy potentials leads to higher RES shares. However, in the High-RES decentralized scenario the curves flatten more in the range from 20 to + 80%, indicating that greater availability of bioenergy is not influencing the results as strong as in the centralized scenario. This has two reasons. Firstly, the RES share is already very high in the baseline situation (ca. 70 and 76% in 2040 and 2050, respectively). Secondly, some peak load capacities exist (e.g., gas-fired or electric boilers) which are not viable or even sometimes technically impossible to be replaced by RES-based technologies.

The main insight of this sensitivity analysis is that if the EU member states are following the pathway described in the High-RES decentralized scenario, then the existing bioenergy potential is sufficient to fulfill the future needs for the district heating generation sector. In contrary, in case of the High-RES centralized scenario, which foresee the growth of district heating demand, the current biomass potential limits the growth and new bioenergy supply sources are required to increase the RES share.

12.4 Conclusion

The future district heating demand varies according to the considered REFLEX scenarios. The district heating demand is the lowest in High-RES decentralized and the highest in the High-RES centralized scenario. In case of the High-RES centralized scenario, the increased district heating demand has to be associated with developments of new district heating systems.

The presented results show that in the future existing heat only plants are being replaced by CHP plants. Bioenergy (mainly biomass) based CHP capacities are increasing (most significantly in the High-RES centralized scenario). This increase, however, can be constrained by the limited biomass potential. Biomass can play an important role in substituting fossil fuels in district heating generation, in particular in the EU member states where the district heating networks are already well developed. Therefore, the transition toward higher use of bioenergy (mainly biomass) requires sustainable organizational (logistic) solutions that minimize energy and CO_2 emissions embedded in processing and transportation. Natural gas is still used to some extent. These results are in line with the outcomes of the "high efficiency" scenario presented in (Cogen Europe 2011) in which RES (mainly bioenergy) constitute two third in primary energy consumption in 2050, and one third is provided by natural gas. Seasonal heat storages and short-term heat storages help to smooth generation profiles and increase the heat production in summer time. Power-to-heat technologies in the TIMES-Heat-EU model include large-scale heat pumps and electric boilers. The former operate more constantly within seasons, whereas the latter actively respond to electricity price variations and generate district heating that can be stored. The use of PtH technologies helps to manage RES electricity surpluses that otherwise would be curtailed.

With decreasing district heating demand on the one hand and with a simultaneous increase in electricity demand on the other—as in case of High-RES decentralized scenario—it is impossible to maintain the current relative share of electricity produced in cogeneration while meeting the cogeneration efficiency requirement. In fact, in this scenario this share decreases from the current 12 to 7% in 2050. In general, district heating costs are increasing in future years. This is mainly due to the investments in new capacities, rising prices of CO_2 emission allowances, and increasing fuel prices. Therefore, it is necessary to maintain the existing or newly implemented policy measures that will guarantee necessary profits for generators and keep the district heating end-user prices at competitive levels (in particular in member states where cogeneration plays a significant role). Only then, it will be possible to have an increase in district heating demand as shown in the High-RES centralized scenario. With the development of low-energy buildings, district heating networks should be expanded in regions where sufficient spatial heat density exist, in order to maintain the current district heating demand. Otherwise with decreasing district heating demand, as e.g., in case of the Mod-RES and High-RES decentralized scenario, CHPs are exposed to lower district heating and electricity sales, what leads to less favorable economic conditions for investors.

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Part V

Analysis of the Environmental and Socio-Impacts beyond the Greenhouse Gas Emission Reduction Targets

Chapter 13
Unintended Environmental Impacts at Local and Global Scale—Trade-Offs of a Low-Carbon Electricity System

Maryegli Fuss and Lei Xu

Abstract The focus on expanding the sector coupling and binding the electricity system and end-user sectors like the transport and industry bring attention to environmental trade-offs. Otherwise, unintended environmental impacts could potentially impede the transformation process. Given that, this paper aims to identify and discuss environmental burdens that should require government attention. For that, the approach of coupling Life Cycle Assessment with the electricity market model (ELTRAMOD) is presented. Results show that the large impact on land use occupation as a regional issue requires attention due to diversified permitting mechanisms and eligibility criteria for solar fields among European member states. Metal and ozone depletion bring the challenge that transformation processes need attention on global limits related to finite resources and fugitive losses of anthropogenic substances.

13.1 Introduction

Fossil-based electricity systems meet, among other criteria, the security conditions of a power outage for many energy-intensive sectors (e.g., residential and tertiary) in Europe for many years. The transition toward low-carbon energy sources (European Commission 2018c) focuses on expanding sector coupling. Now the critical issue is to bind the electricity system and the two largest fossil fuel combustion sectors, transport, and industries (cf. Part III and IV). The challenge going forward is to maintain the security of supply of the electricity sector (including transport and industry sectors) and at the same time to achieve specific decarbonization targets (cf. Chapter 2).

The embedded carbon emissions are becoming more and more discussed between researchers. For instance, there is a debate about the biases of a clean conceptual approach for greener mobility through electric vehicles when the energy in-use source is an oil or coal-based power plant (Clarke 2017; Egede et al. 2015; Holloway 2019).

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Indeed, there is no doubt that the electricity system has to undergo a radical transformation as the leading sector to reshape the entire European energy system (European Commission 2018c). Under these circumstances, the electricity system became the core sector that requires an in-depth analysis in the REFLEX project.

Among the REFLEX scenarios (cf. Chapter 2 and Poganietz et al. 2017; Zöphel et al. 2019), combustion emissions affecting climate change such as CO_2, CH_4, N_2O, and so on, have the potential to be reduced significantly, if wind and solar technologies are deployed on a very large-scale in Europe. Moreover, decarbonizing the electricity sector will facilitate significant reductions in carbon emissions due to industry, transport, residential, and tertiary sectors. Part III and Part IV of this book describe how carbon targets could be achieved within the scope of the REFLEX scenarios.

Developments aiming at reducing greenhouse gas emissions from the electricity sector may nevertheless cause increases in other kinds of environmental impacts. Costa-Campi et al. (2017) also stress that energy policies usually focus on the political economy dimension, which could bring conflicts with the goal of environmental protection. It is necessary to be aware that the transition of the energy system depends on many techno-economic features such as the massive penetration of renewable technologies that are still not in place in some countries and the need for low-carbon emission fuels like natural gas (cf. Chapters 10 and 11). All these developments could drive critical environmental impacts on the European scale (i.e., local effects), but also globally due to the reach of supply chains. Although discussions at the political level have expanded to include broader sustainability-related considerations, imposing protection conditions for ecosystems and human health, for example, Europe still gears its policy toward carbon-based benchmark regulation exclusively (European Commission 2019a).

The objective of the present Chapter is to identify and discuss unintended environmental burdens based on the envisaged REFLEX scenarios that require further policy action. Unintended environmental burdens are impacts that are driven by a critical problem that could impede a smooth transition to the decarbonized European energy system. Based on the methodological framework developed in the REFLEX project (Brown et al. 2017; Brown et al. 2019), this paper applies the model coupling approach (cf. Chapter 3). It focuses on the process of coupling Life Cycle Assessment (LCA) with the bottom-up electricity market model (ELTRAMOD), the chosen energy system model for this study. The model coupling between LCA and ELTRAMOD brings the advantage of quantifying a full range of environmental impacts and therefore the possibility to discuss environmental trade-offs of the three REFLEX scenarios, Mod-RES, High-RES decentralized, and High-RES centralized (cf. Chapter 2 and 10).

The structure of this paper is therefore as follows:

- Describing the model coupling approach to analyze scenarios for the electricity system (Sect. 13.2);

- Describing and discussing the unintended environmental consequences of the European low-carbon electricity system at member states level and globally (Sect. 13.3);
- Conclusions and formulating policy implications (Sect. 13.4).

13.2 Developing the Model Coupling Approach to Identify Environmental Trade-Offs

For the REFLEX project, three fundamental aspects are taken into consideration in electricity production systems:

1. The need for new infrastructure: The transformation of the electricity sector is a gradual process that will require, among other developments, new infrastructure to facilitate deployment of large-scale renewable technologies that are not in place yet.
2. Innovative technologies: They are technologies for exploiting intermittent energy sources, e.g., wind and solar. Wind turbines and solar photovoltaic cells provide examples of how industries are rapidly changing. Many of them have similar competitive perspectives, such as to offer the most efficient product with low maintenance costs, and low resource demand (Froese 2019; Gandenberger 2018).
3. Less emission-intensive fossil fuels: The European Union has always taken necessary precautions in the area of fuel supply, especially concerning fossil energy resources. For instance, there is an ongoing focus on natural gas supply in the EU policy (Correljé 2016).

LCA and ELTRAMOD have a different objective function. While LCA is focused on environmental impacts modeling, ELTRAMOD is an electricity market model (cf. Chapter 10). This study follows the detailed procedures described by Xu et al. (2019). Firstly, inputs for the LCA model are based as closely as possible to the REFLEX scenarios (Chapter 2) in line with (1) and (2). Secondly, the LCA model is adapted to the technology groups used by ELTRAMOD. ELTRAMOD considers conventional and renewable technologies and a low-carbon group representing installed capacities of fossil fuel-fired carbon capture and storage (CCS) technologies (cf. Chapter 10), bringing attention to a policy aimed at securing fuel supply (3).

This study recognizes several challenges and barriers to producing LCA results that match public policy development (Hellweg and Milà i Canals 2014; Seidel 2016). For instance, transparency and accurate inventories are often questionable among non-practitioners. To establish a common understanding, the most significant inputs and adjustments for the model coupling are presented below.

13.2.1 Describing Relevant Input Parameters for the LCA Model in Context of the REFLEX Scenarios

Transparency of input data for the LCA model is important to support robust conclusions. In the REFLEX project, identification of specific technology types is the starting point for ensuring that future supply needs (e.g., resources and fuels) are considered. The challenge is to include scenario-based considerations in establishing life cycle inventory for future energy technologies over their entire lifetime (including extraction of raw materials, manufacturing of new technologies, transportation and installation, generation of electrical power to the grid and end-of-life).

The future market share of innovative and conventional technologies is a parameter directly connected to the REFLEX scenarios. The study of Viebahn et al. (2015) provided a technological roadmap and bandwidth extrapolations based on a search of all renewable energy technologies existing in energy scenarios in Germany. Additionally, this study analyzed possible future developments of renewable energy technologies based on literature and expert knowledge. However, the market share parameter defined by Viebahn et al. (2015) is only applied in this study for wind and solar technologies that are currently accepted or emerging on the market. Technologies on the laboratory scale are not included. Wind power technologies are represented in the LCA model by four different turbine types (asynchronous generators, electrically excited direct drive, permanent magnet, and superconductor high-temperature) and solar power is represented by two types of photovoltaic cells (crystalline cells and thin-film cells).

The LCA model and ELTRAMOD have common techno-economic parameters. The approach for parameter harmonization in REFLEX (Fuss et al. 2018) required coordination of techno-economic characteristics of technologies (e.g., installed capacity, lifetime, and efficiency) to increase the consistency among the models. Techno-economic parameters provide, for example, the possibility to quantify resource demands for each technology according to the capacity expansion paths assumed in ELTRAMOD.

Figure 13.1 shows generic inputs and outputs for the transition of the electricity system in Europe. Although the goal is to make the electricity sector cleaner and provide better environmental conditions in Europe, attention should be paid to consequences at a global scale too. It should be noted that outputs of the transition should achieve goals according to the European commitment within the sustainable development goals (European Commission 2019c) such as to safeguard life on land and secure good health and well-being.

Figure 13.1 also shows fuels, resources, and entire technologies imported to Europe from the global market. This study assumes that these resources, fuels and technologies are produced in the global market. This assumption is based on the fact that the EU is in favor of free trade and does not make exceptions to this for energy technologies and related markets (European Commission 2018b). With respect to fuels, the LCA model considers the exploration (or cultivation for biomass) and production at supplier location as a first stage. The supplier countries commitment

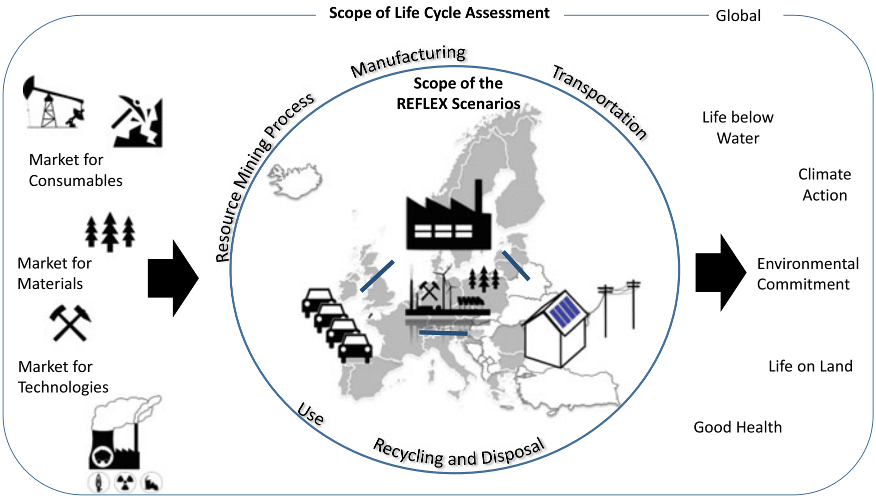

Fig. 13.1 Example of inputs and outputs required for electricity production (*Source* Own illustration)

ends after the transportation of the fuel to local and large-scale power plant distribution in Europe, the second stage considered in the LCA modeling. Due to significant uncertainties about future developments, it is assumed that the share of the global suppliers (i.e., European supplier leading countries) does not change in any of the REFLEX scenarios.

The entire inventory analysis makes use of the ECOINVENT 3.3 database, which provides well-documented foreground process data (Wernet et al. 2016). For each emerging technology, a new inventory database is established based on resource inputs and electricity demand for production. Details of the life cycle inventories for all technologies considered and the respective ECOINVENT data processes used are available in Brown et al. (2019).

13.2.2 Coupling the Results of ELTRAMOD and the LCA Model to Determine Policy Implications

Figure 13.2 illustrates the procedure used in this study from coupling the results of ELTRAMOD through to the identification of relevant policy implication. Step 1 consists of coupling the described LCA model (Sect. 13.2.1) with results for electricity generation mix generation produced by ELTRAMOD. Equation 13.1 summarizes the model coupling calculation method:

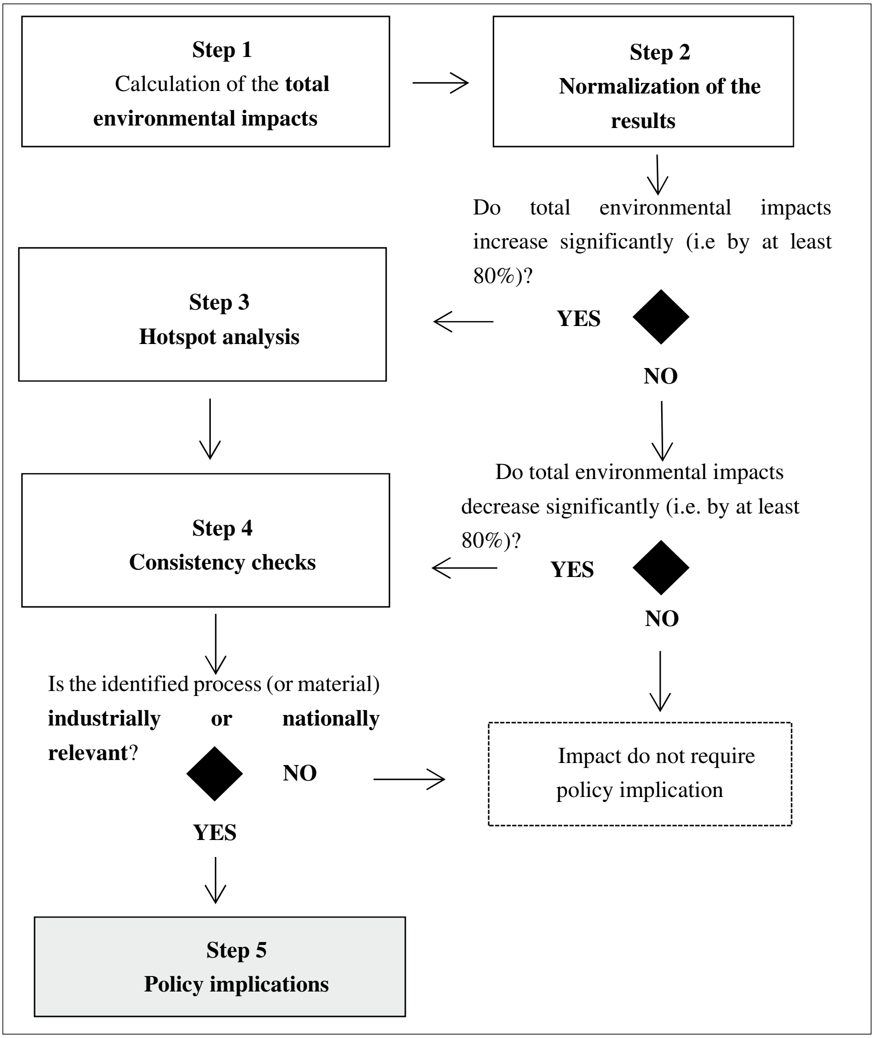

Fig. 13.2 Systematized procedures for extracting LCIA results for policy guidance (*Source* Own illustration)

$$Z_{n,t} = \sum_{T=1}^{n} LCIA_{T,n,t} * ET_{T,t} \tag{13.1}$$

where Z_n is the total environmental impact in category n over the life cycle of an energy technology group of all modeled countries, i.e., EU-27, Norway, Switzerland, United Kingdom, and Balkan countries in period t measured in the respective unit, e.g., in case of metal depletion, $t\ Fe_{eq}$ (ton iron equivalent), $LCIA_{T,n,t}$ is the environmental impact of an energy technology group in period t measured in the respective unit, e.g., $t\ Fe_{eq}$, per TWh. $ET_{T,t}$ equals the electricity generation of the energy technology group in period t in TWh. For instance, ET_{wind} represents the group of specific technologies T as previously described (e.g., synchronous generators, and asynchronous generators).

Step 2 consists of normalization to evaluate 18 different impacts categories according to the RECIPE life cycle impact assessment (LCIA) method (Goedkoop et al. 2012) that is used in the REFLEX project. In this step, the calculated results in each scenario and the respective temporal cases are divided by the base year (2014). In this way, it becomes possible to screen for the most relevant impacts for each scenario. The screening analysis aims to identify those environmental impacts that overtook the threshold defined by the modelers. The threshold of 80% reduction or increase was chosen. The value of the index is comparable to the climate target. Hence, unintended environment burdens are identified when the environmental impacts increase significantly (by at least 80%).

In-depth analysis of unintended environmental burdens is performed in step 3. The largest contributors (drivers) to these impacts are analyzed in terms of the most critical technology from the electricity production mix, life cycle stage, processes, and flows.

The level of uncertainty is one of the barriers to trust in LCA results, as mentioned by non-practitioners and decision makers (Seidel 2016). Sensitivity analyses, mapping characterization, and classification factors applied or not in the RECIPE method, double-checking with different LCIA methods were conducted as part of step 4 of the method (i.e., consistency checks).

Up to step 4, the used procedure follows the usual procedures that are taken in LCA modeling to derive robust conclusions (Zampori et al. 2016). Step 5 is added exclusively for this study. The objective of step 5 is to assess the findings of the LCA model from the perspective of current policies and national and industrial priorities as considered in the literature.

A comparison with current policies supports the discussion of identified drivers (e.g., technology or flow) is the trade-off that can impede the achievement of the climate target if no intervention is made.

The policy implications should be seen as precautionary information aiming to raise awareness about potential trade-offs and related environmental consequences without further policy intervention.

13.3 Unintended Environmental Consequences of the European Low-Carbon Electricity System

According to the 2014–2050 REFLEX scenarios, results are presented for the total environmental impacts due to the total electricity generation in EU-27, Norway, Switzerland, United Kingdom, and Balkan countries (Chapters 2 and 10 and Zöphel et al. 2019) for a given temporal case. The absolute environmental impacts are presented (instead of the normalized results) for better comprehension of the findings discussed. They are introduced at an aggregate level as a final output of the schematic workflow, instead of describing the findings for each step (c.f. Figure 13.2) and each generation technology (Chapter 10). The overall impacts due to the REFLEX scenarios (step 1 and 2) are presented in Brown et al. (2019).

13.3.1 Environmental Impacts at Local Scale and the Challenges for European Member States

Land use is an environmental trade-off arising for the low-carbon electricity systems in the REFLEX scenarios. Figure 13.3 shows the absolute land use for the development of the overall electricity generation according to the envisaged scenarios.

Increasing demand for ground-mounted photovoltaic (PV) is responsible for increases in land use for all scenarios. According to Fig. 13.3, High-RES scenarios show a dramatic increase in land use, by a factor of nearly five over the base-year, reaching 32,630 km^2·a (High-RES cen) and 33,724 km^2·a (High-RES dec). In particular, between the years 2020 to 2040, the impact on land use occupation is a consequence of the changing mix of technologies used for electricity generation. While coal-based generation is replaced (among other technologies) by the increasing capacities of ground-mounted PV (and wind energy), land use impacts

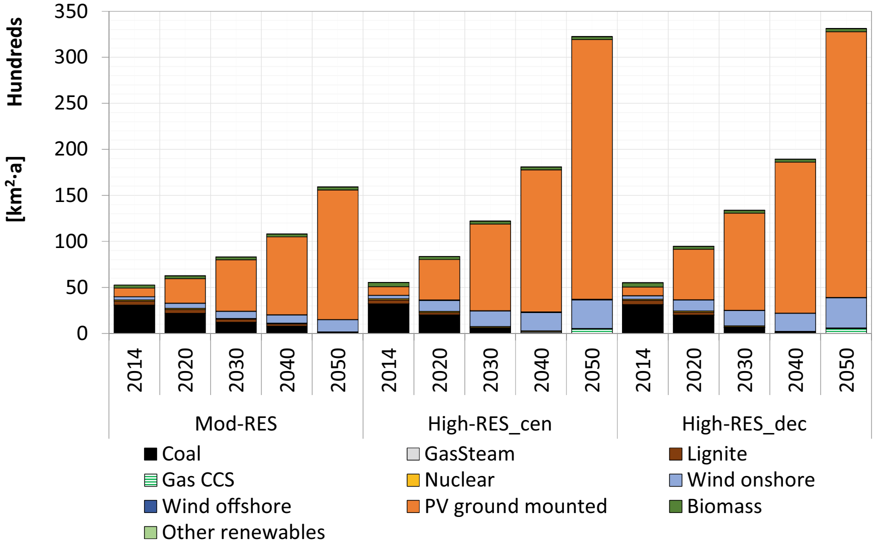

Fig. 13.3 Major technologies contributing to the land use impact of the overall electricity generation in EU-27, Norway, Switzerland, United Kingdom, and Balkan countries (*Source* Own illustration)

increase. In the period 2040–2050, land use impact doubles due to measures aiming to achieve the target to electrify the transport and industry sectors.

For comparison: the direct land use for coal-based generation is 4.5 km^2/TWh compared to an average of 47.8 km^2/TWh for ground-mounted PV. Indirect impacts due to coal surface mining are not taken into account. In contrast, the estimated land use of 2.5 km^2/TWh for wind technologies is relatively low.

In the RECIPE impact assessment method, the land use category "land use occupation" avoids any other trade-offs for land used for food and the conservation of the ecosystem. The results above represent this category. It is assumed that no land transformation from one status (e.g., forest) to the other (e.g., agricultural land) will occur. Therefore, competitions, which still might happen as a consequence of land used for urban expansion or even a delay of restoration to the prior nature conditions, cannot be excluded (Goedkoop et al. 2012).

Although land use seems not to be a significant environmental problem, the results indicate that 28,864 km^2 of land (equivalent to over 70% of the total area of Switzerland) would be required for solar fields in 2050 in the High-RES decentralized scenario. The requirement is similar for the High-RES centralized scenario, as shown in Fig. 13.3. This is because the electricity mix is very similar in both scenarios (Zöphel et al. 2019). In any of the cases (centralized or decentralized), it should be noted that 56% of the total area requirement for solar electricity generation is potentially aimed for solar fields between 2040 and 2050.

As part of the European SET-Plan, the deployment of ground-mounted PV will increase in European member states (European Commission 2018c). Italy, France, and Spain are the EU countries with the highest potential for technology due to proper climate conditions, among other criteria. The European standard classification, defines land use division into agricultural land, forest and "other" (this category includes built-up areas, roads and other transportation features, barren land, or wasteland) (CIA World Factbook 2018). If the installed capacity (demand) are taken into account according to High-RES decentralized scenario, it will require over 9% of the "other" category of land in Italy, 12% in Spain, and 4% in France. Those three countries have diversified permitting mechanisms and eligibility criteria for ground-mounted PV plants. In France, implementation conditions for ground-mounted PVs are under discussion where bonus could be accepted if wasteland (e.g., landfills, industrial brownfield, and polluted area) would be taken (Bozonnat 2018). However, the French Act on Energy Transition (France 2015) stands only on the market segment for PV rooftop installations. Meanwhile, in Italy, large solar fields require a process authorization that is still not clearly defined. Within the authorization process, the Italian government aims to minimize agriculture land losses and guarantee their aesthetic green power system (Bellini 2019). Ground-mounted PV fields are well accepted in Spain. The country eliminated all constraints that could impede the deployment of renewable technologies in the national legislation since 2014 (Morales 2018). The free-deployment legislation could be attractive for investors. Therefore, Spain is facing the highest urban growth rate in the EU (URBACT 2019). Competition in Spain between urban development and space for ground mounted solar PV could be a future challenge, especially since there is only a small amount of land in the category "other."

However, Italy, Spain, and France are examples of countries where regulations could impede the transition to renewable energy based on ground-mounted PV plants.

13.3.2 Resource Depletion in REFLEX Mitigation Scenarios as a Backdrop of Global Trade Uncertainty

Metal depletion, owing to the research focus on innovative technologies (cf. Sect. 13.2), calls for in-depth analysis of the availability of finite resources. At the same time, the shift to natural gas-based carbon capture and storage electricity generation requires attention to ozone depletion due to emissions of ozone-depleting substances in natural gas supply chains. In light of these considerations, metal and ozone depletion impacts are presented in the following sections.

13.3.2.1 Metal Depletion

Another consequence of the electrification of the industry and transport sectors to reach the climate targets (cf. Chapter 6, 7 and 10), is the trade-off on metal depletion. Figure 13.4 shows that regardless of the scenario or year, metal depletion increases due to increased solar and wind energy generation. The high share of wind and solar electricity generation in the High-RES decentralized scenario (to achieve, for instance, the demand for hydrogen production in industry and transport in 2050, cf. Zöphel et al. 2019) increases the metal depletion impact to over 290% compared to the year 2014. Meanwhile, in the Mod-RES and High-RES centralized scenario, the growth is about 75 and 235% for the same period, respectively.

Metal depletion is estimated to be 19,530 tFe_{eq}/TWh for wind onshore, 25,900 tFe_{eq}/TWh for PV rooftop compared to 4,140 $MtFe_{eq}$/TWh for nuclear power plants. Chromium steel, low-alloyed steel, reinforced steel (for towers, rotors, and nacelles) as well as copper for connecting wires together contribute to over 90% of the metal depletion for onshore wind generation. In spite of the fact that industries are seeking to minimize the demand for silver in crystalline PV manufacturing (ITRPV 2018), rooftop PV generation indicates the highest metal depletion impact where the major contributors are copper (58%), gold (7%), steel (4%), and silver (1%). Among those metals, recycling activities are intensively done only for steel.

In a sensitivity analysis, the possibility of steel recycling was taken into account. The results shown in Fig. 13.4 are based on the assumption that all metals are primary resources, i.e., obtained directly from mining activities. Nowadays, about 80% of steel is recycled globally (BIR 2018). With a hope that steel recycling could reach 90% until 2050, the burdens of metal depletion for electricity production in the High-RES centralized scenario can be reduced by 40% according to the sensitivity

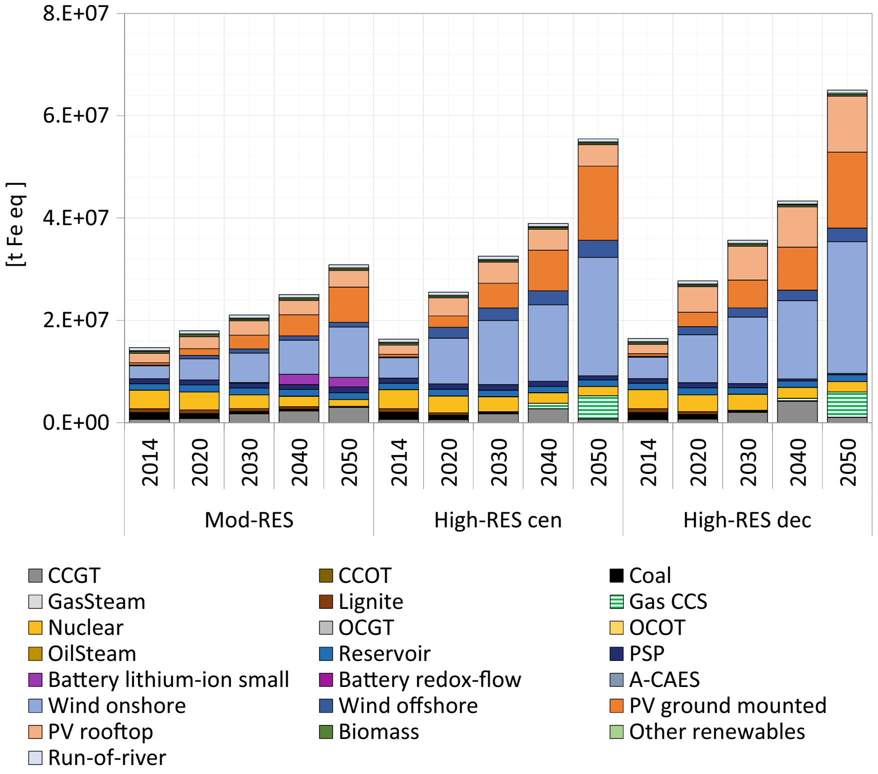

Fig. 13.4 Major technologies contributing to metal depletion impacts due to total electricity generation in the EU-27, Norway, Switzerland, United Kingdom, and Balkan countries. Abbreviations: CCGT (combined cycle gas turbine), PSP (pumped-storage power plants), Gas CCS (gas carbon capture and storage) (*Source* Own illustration)

analysis. It should be noted that recycling indexes for other metals are lower than 50% (e.g., copper) or even non-existent in the EU (e.g., silver) due to small quantities in electronic facilities (Hagelüken et al. 2016).

The challenge regarding metal depletion is that metals are non-renewable resources comparable to fossil fuels. The environmental impact indicates the reduction of availability of a specific group of resources (commodities). The assumption lies in the mining costs as the dominant and consistent factor between dissimilar metals in the RECIPE method (Goedkoop et al. 2012).

In the model applied, innovative wind and solar technologies (Sect. 13.2.1) are distinguished from the conventional ones according to the new resources required for their manufacture. Ten metals are additionally included for these technologies in this study, namely, neodymium, praseodymium, dysprosium, gadolinium, and cobalt for emerging wind turbines and cadmium, selenium, tellurium, gallium, and indium for thin-film solar cells. In the consistency checks (step 4, cf. Figure 13.2), it is observed that those metals were not assessed in the results presented in Fig. 13.4. The main reason is the missing characterization factors in the RECIPE method.

Following the same assumptions as presented in the RECIPE method, for example, the weighting factor of platinum is taken for neodymium. Platinum represents the highest mining costs with over 11,000 USD/kg in the RECIPE method (Goedkoop et al. 2012). Neodymium is rare and often hard to find, which would therefore be comparable to platinum. It is a rare earth metal belonging to a group of 15 different elements which together represent 5–10% of a mineralized rock (monazite). It is extracted from open-pit mining mainly located in China. Nowadays, due to several challenges such as environmental issues, illegal mining, and export, the Chinese government are implementing policies such as mining quotas (Mancheri et al. 2019). Neodymium is nevertheless an essential resource for wind turbines with high power output and large blade sizes (Vestas 2019). Taking the most ambitious REFLEX scenarios (High-RES scenarios) as an example, considering the framework conditions, the demand for neodymium alone would contribute to 95% of the total metal depletion for wind power. If neodymium would be included in the RECIPE method, it would lead to the greatest single inventory contribution in the metal depletion impact category.

Although the results for metal depletion are highly dependent on the technologies (Sect. 13.2.1) and resources previously described, there is no doubt that wind and solar technologies are highly competitive in the global market. Many European companies are strongly recognized on the market for wind technologies, such as Denmark's Vestas and Spain's Siemens Gamesa, which are behind China's Goldwind, the world's largest wind turbine companies (Froese 2019). Meanwhile, Chinese industries have taken the lead in photovoltaic manufacturing due to strengthened innovation efforts in the country (Gandenberger 2018). Thus, availability and access to the resources considered in this study will be a major factor to ensure the necessary commercial development and to achieve the envisaged targets for the transformation of the electricity system.

Secure access to resources and resource efficiency are objectives identified in the EU 2020 strategy (European Commission 2011). Nevertheless, metal depletion is a trade-off for climate targets as problems arise due to high metal demand (e.g., steel) and the high amount of non-recyclable metals.

13.3.2.2 Ozone Depletion

The High-RES scenarios show how high CO_2 prices will potentially require low-carbon energy sources (e.g., nuclear power plants) and accelerating the deployment of the natural gas generation with carbon capture and storage (CCS) from 2040 onwards (cf. Chapter 10). An outcome of these developments is an increase in ozone depletion impact, as shown in Fig. 13.5.

Ozone depletion brings consequences for humans globally (e.g., excess skin cancer incidence) because of ozone layer destruction through fugitive losses of anthropogenic substances (Goedkoop et al. 2012; Velders et al. 2000). One of the

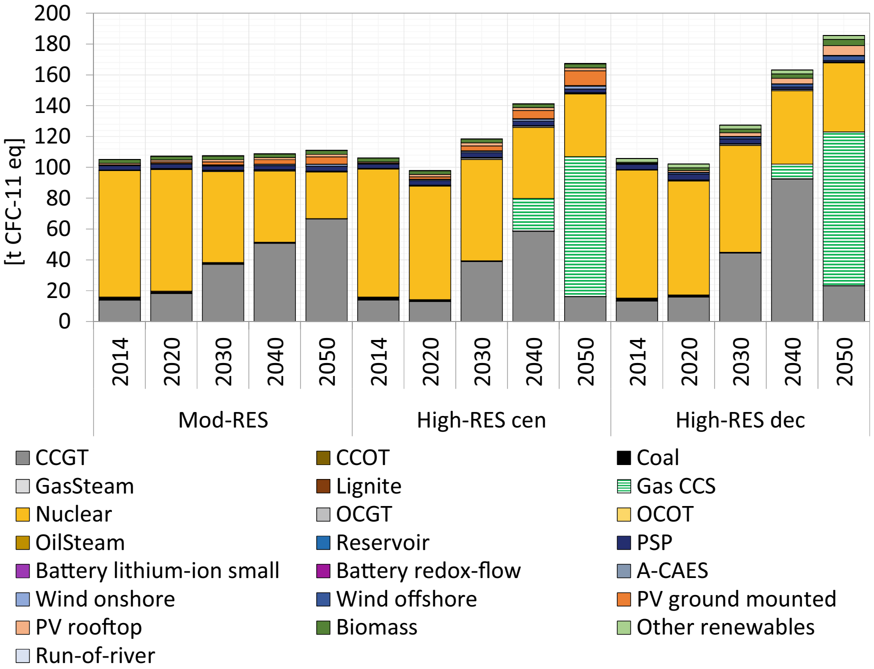

Fig. 13.5 Major technologies contributing to ozone depletion in overall electricity generation in the EU-27, Norway, Switzerland, United Kingdom, and Balkan countries (*Source* Own illustration)

global responsibilities assumed by the EU is the Montreal Protocol that aims to protect the ozone layer by identifying hotspots where ozone-depleting substances might occur (EEA 2018). With this consideration in mind, two aspects of the ozone depletion results from the analysis of the REFLEX scenarios are presented (cf. Figure 13.5):

- **Mod-RES scenario (2014 vs. 2050):** The magnitude of the ozone depletion impact remains approximately constant, but the contribution share is shifting according to the change in generation mix from nuclear to combined cycle gas turbine (CCGT).
- **High-RES scenarios (2014 vs. 2050):** The rapid increase of the ozone depletion impact is accompanied by the rise in power generation of natural gas CCS.

The transportation of natural gas, as fuel for CCGT and natural gas CCS generation, is the specific activity contributing to ozone depletion according to the life cycle phases connected to the supply chain. The identified problem arises due to leaks of methane and hydrocarbons in the pipelines from Russia, as the major natural gas supplier for Europe. Europe imports 40% of natural gas from Russia, 38% from Norway, 11% from Algeria, 4% from Qatar, and others (Eurostat 2019).

Transport of natural gas releases leakage nowadays (ICLG 2019; Healing 2018; Nasralla 2020). Pipeline leaks are a complex environmental problem for local supplier countries. Leakage of natural gas consists primarily of methane and ethane, and both are drivers for photochemistry reactions and non-linear interaction in the stratosphere-troposphere (Portmann et al. 2012; Velders 1997; Velders et al. 2000). Bromochlorodifluoromethane (Halon 1211) and Chlorodifluoromethane (HCFC-22) are two critical substances identified in the modeling analysis. These two substances are released in the stratosphere-troposphere due to other past and current industrial processes (Portmann et al. 2012). The concentrated amount of natural gas leakage may attack chlorine and bromide from Bromochlorodifluoromethane (Halon 1211) and Chlorodifluoromethane (HCFC-22) (Velders 1997; Portmann et al. 2012). Such reactions impede the future evolution of the ozone (Velders 1997; Portmann et al. 2012).

Additionally, the increasing demand for natural gas and continuous leakage problems can degrade regional air quality and are bad for human health (cf. Chapter 15, Velders et al. 2000). Moreover, the effects imposed on the supply chain of natural gas already bring new awareness that is connected to the problem of pipelines identified in this study. Among several issues, geopolitical changes are influencing the natural gas market (Correljé 2016) and can slow the pace of climate targets in Europe, if the electricity mix will be dependent on CCGT or gas CCS technologies. Furthermore, many Russian pipelines have exceeded their operational lifetime (Nasralla 2020). Thus, significant investments are needed to comply with new regulations, such as the installation of electromechanical corrosion protection of pipelines, technological communication facilities, leak identification, and warning systems (ICLG 2019; IEA 2006). Meanwhile, Norwegian companies are working on better sealing technologies because leakages are not visible in the stormy and cold North Sea by monitoring systems which leads to problems for the supply chain (Healing 2018). However, an environmental challenge exists for many European countries, especially Germany, that needs to import more natural gas as a substitute for the coal-based electricity generation.

Although industries and nations are already facing the challenge, it is still not clear how countries (exporter or importer) will divide the responsibility for judging the compliance to diminish pipeline leaks. Until no bilateral commitment is aimed, great demand for natural gas has the potential to enhance ozone depletion causing regional effects and trade-offs for the achievement of climate targets.

13.4 Conclusions and Policy Implications

The electrification of end-user sectors and the simultaneous decarbonization of the electricity system are ambitious targets for the European Union. This sector coupling approach is a key element in the transition to a fossil-free economy. From an environmental perspective, a successful sector coupling is highly dependent on the development of the electricity system. Moreover, the reduction of greenhouse gas emissions by 80% for the electricity sector requires, among other things infrastructure planning, availability of technologies that are ready at a convenient time and environmentally friendly low-carbon emission fuels. Otherwise, three environmental impacts, identified in this paper, could impede the transition process for a low-carbon electricity system. Land use requires infrastructure planning among EU member states with different regulations. The results concerning the assessment of metal depletion demonstrate that the transformation process to a low-carbon electricity system is highly dependent on the availability of metals (finite resources) to produce technologies for intermittent electricity generation. The outcomes of the analysis regarding ozone depletion highlight the potential effects of fugitive losses that affect anthropogenic substances (e.g., Halon 1211 and HCFC-22 identified in this study) and are an issue for global suppliers of natural gas. This impact additionally leads to the demand for further international agreements (such as the Montreal Protocol) to protect the ozone layer.

The results are created through the schematic work and method described in this study. They build upon the model coupling of LCA and ELTRAMOD to assess the REFLEX scenarios. The outcomes are highly interconnected to the assumptions made and the LCA modeling. Therefore, this study includes a methodological description to promote transparency and robustness to the results. However, the analysis of potential environmental impacts of the energy transition increase awareness and identify new research areas.

Through the LCA modeling, it is identified that the deployment of ground-mounted PV technologies has a crucial environmental impact. Land use for ground-mounted PV in the base year (2014) amounts to only 3% of that required in 2050 for the High-RES decentralized scenario—950 km^2 compared to 28,864 km^2 (cf. Figure 13.3). Countries with best weather conditions for ground-mounted PV power plants (like Italy, Spain, and France) consider restrictions concerning aesthetic requirements as well as potential resident opposition (NIMBY—not in my back yard). Although data show, the availability of other lands for ground-mounted PV installation (cf. Section 13.3.1), society and legal systems could impede such developments. Considering these constraints would require a break-down of regulations and infrastructure planning among EU member states and continuous investment in research at local scales. Investment in research and innovation opens opportunities for solar energy. Hoffacker et al. (2017) present how PV systems enable techno-ecological synergies in the United States, for instance, the utilization of a reservoir power plant for solar electricity generation ("floatovoltaics") and PV systems integrated in agricultural landscapes (agro-photovoltaics). In Europe, few agro-photovoltaic projects have been implemented and still need to deal with agronomic challenges like the field management on crop production (Weselek et al. 2019).

A more tightly integrated Europe, not in political terms but rather with respect to technology development and supply markets, would help to address the challenges related to metal and ozone depletion. For instance, the transformation of the entire European electricity system depends mostly on the commitment of member states, where some countries will probably set up more ambitious targets than others. Consequently, these members will require a higher commitment to deploy innovative renewable technologies similar to those studied in this chapter, such as permanent magnet and superconductor high-temperature wind turbines. Contrary to the current free-market orientation on the openness of trade (European Commission 2018b), the proximity of renewable technology industries with the EU could bring advantages for both sides. In this regard, the EU could support even more local industries to address the fluctuation of resource prices and trade import tariffs, although Europe has one of the lowest trade import tariffs in the world (European Commission 2019b). On the other hand, industries could provide more information about how the required resources are affecting the global environment. Because the supply chain for crucial resources of wind technologies involves intense mining activities causing strong vulnerability due to regional impacts on the environment (Ballinger et al. 2020).

The assessment results presented in this study confirm that natural gas will be the most significant contributor to European energy security in the upcoming future, replacing oil and coal energy sources (Correljé 2016). Germany, for instance, has assumed a National Preventive Action Plan and Emergency Plan with regard to natural gas and has taken the responsibility to be the European business location for natural gas (European Commission 2018a). However, stockpiling of natural gas could be the most attractive alternative to guarantee desired fuel stocks, along the lines of a similar procedure adopted by Germany for petroleum (European Commission 2018a). Therefore, further commitments by supply and demand countries regarding global impacts (ozone depletion) would additionally create incentives between the natural gas sectors to promote dialogues and foster investments (e.g., renovation, research, and innovation) for an environmental friendly low-carbon fuel.

This study identifies and discusses policy implications related to three environmental trade-offs in the context of a low-carbon electricity system: land use occupation, metal depletion, and ozone depletion. Many contributing factors to the unintended environmental burdens (trade-offs) are technically known. However, the factors are still not discussed as an obstacle for the European electricity transition. The development of any strategy to deal with these environmental trade-offs should bring local industries, member states, and the EU together.

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Chapter 14
Assessing Social Impacts in Current and Future Electricity Production in the European Union

Nils Brown and David Lindén

Abstract In this chapter social impacts of European electricity production are compared between the current situation and the REFLEX scenarios for 2050 from a life cycle perspective using the SOCA tool. The analyses indicate that for a limited number of social impact categories the SOCA add-on tool can identify geographic locations where improvement in social performance may non-negligibly improve the social impacts for future energy systems. Results show that gas supply from Russia is a major cause of social impact for all future scenarios in the subcategory "fair salary" due to the fact that the minimum wage is below the living wage in the country. The specific process for electricity generation in Europe contributes to social impacts in the same category to a lesser extent.

14.1 Introduction

The development of environmental life cycle assessment (eLCA) as currently practiced is often traced back to the early 1990s. Meanwhile, only in the past decade interest has been directed toward using a life cycle perspective to perform social assessments—so-called social life cycle assessment (sLCA).

A major step in the methodology's development was the publication of the sLCA Guidelines (UNEP 2009). The technical framework for sLCA is based on the structure of the eLCA standards (ISO 2006a, 2006b), considering goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation (UNEP 2009). Among other things, the Guidelines identify a set of stakeholder categories each of which cluster a group of different stakeholders that "are expected to have shared interests due to their similar relationship to the investigated product

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systems” (UNEP 2009, p. 46). The stakeholder categories so identified are workers, local community, society (national and global), consumers and value chain actors.

The years since the publication of the Guidelines have seen a certain amount of research activity in the field, as testified by recent review papers (Arcese et al. 2018; Dubois-Iorgulescu et al. 2018; Zanchi et al. 2018). Databases have also been developed that collect social performance data for several products, product systems and functions for a wide variety of social contexts, where leading examples are the social hotspots database (Benoit-Norris et al. 2012) and the product social life cycle assessment (PSILCA) database (Ciroth and Eisfeldt 2016). The SOCA database add-on (Eisfeldt 2017) meanwhile connects the social inventory and impact assessment methods used by PSILCA with the ubiquitous environmental LCI database ECOINVENT (Wernet et al. 2016). Data in the SOCA tool aim to support social assessment from the perspective of four stakeholder categories (workers, value chain actors, local community and society) and 37 connected social impact categories established according to the Guidelines (UNEP 2009). The stakeholder category workers are well-represented in SOCA, covering 18 separate indicators. Having first been made available in 2017, the tool is still quite new and there exist few if any examples of its application in literature, a gap that is aimed to be filled by the work carried out here.

Meanwhile, the aim of the REFLEX project is to analyze and evaluate the development toward a low-carbon energy system in the EU up to the year 2050 to support a better system integration of RES. The central approach in achieving this objective is to perform scenario-based energy economic system modeling (cf. e.g. E3MLab 2016; Fichtner et al. 2013; Fragkos et al. 2017; Herbst et al. 2012; IEA/OECD 2016; Schade et al. 2010 for examples of previous work in the same field).

Though the energy systems modeling performed in REFLEX provides important insights to support the path to carbon neutrality and beyond, the approach in general and REFLEX models specifically do not aim to cover in particular a range of social issues. Nevertheless, EU energy policy is guided by three fundamental principles—security of supply, competitiveness and sustainability (European Commission 2016). Furthermore, the EU is committed to implement the Sustainable Development Goals (SDGs) in internal and external policies (European Commission 2019), including notably significant social issues such as good health and well-being, the elimination of poverty, labor rights, safety at work and fair wages. In light of the intersection of EU energy policy and development policy through the lens of sustainability, it is important to understand how an envisaged future energy system may affect the potential to achieve such goals as exemplified in the SDGs.

Considering the aforementioned ongoing development of methodologies, tools and databases for sLCA and since EU policy is guided simultaneously by the need for transition to a low-carbon energy system and to fulfill the SDGs, the main aim of this chapter is to compare social impacts for EU electricity production between the current situation and the REFLEX scenarios for 2050 from a life cycle perspective using the SOCA tool. Through fulfilling this aim it is intended to provide an example of the application of the SOCA add-on for social assessment and also to formulate policy recommendations for achieving improved social outcomes in the energy system transition.

14.2 Method

14.2.1 *Background to the SOCA Add-on for Social Life Cycle Assessment*

The SOCA add-on tool provides a quantity of worker-hours (the activity variable in social LCA, cf. UNEP 2009) and a social risk profile for each ECOINVENT unit process (as defined by a reference flow and functional unit). This is done in a few steps. Firstly, the sectoral allocation (according to International Standard Industrial Classification, United Nations 2008) and geographical allocation (cf. Mutel 2014) for each ECOINVENT unit process are mapped to the corresponding sectoral and geographical allocations in the PSILCA database, which is in turn based on the EORA database (cf. Ciroth and Eisfeldt 2016). Afterwards, each ECOINVENT unit process can be assigned a social risk profile in terms of four stakeholder categories (workers, value chain actors, local community and society) and 37 connected social impact categories established according to the Guidelines (UNEP 2009). In a second step, cost data given for each ECOINVENT unit process is multiplied by the labor intensity for the sector to which it has been mapped in PSILCA (in worker hours per unit monetary output) to yield an activity variable in worker-hours for each ECOINVENT unit process.

The final impact assessment step is performed by assigning the raw value for a given social indicator a *qualitative* level of risk (varying from no risk, very low risk, low risk, medium risk, high risk and very high risk) each of which is assigned a *quantitative* impact factor. As an example for the purposes of understanding, Table 14.1 shows the procedure for social impact assessment for the social indicator "Disability adjusted life years (DALYs) due to indoor and outdoor air pollution". The left hand column shows the intervals for the raw indicator values for each qualitative level of risk. For example, an ECOINVENT process with a social performance 7.8 DALYs per 1,000 inhabitants (i.e. the raw value of the social indicator) falls between 5 and 15 DALYs per 1,000 inhabitants and is therefore assigned a qualitative level "low risk" according to the central column in Table 14.1. Finally, the qualitative risk level

Table 14.1 Example of semi-quantitative risk assessment for indicator "DALYs due to indoor and outdoor air and water pollution" (Ciroth and Eisfeldt 2016)

Raw value of indicator (y) (DALYs per 1,000 inhabitants)	Qualitative risk level	Quantitative social impact factor
0	No risk	0
$0 < y < 5$	Very low risk	0.01
$5 \leq y < 15$	Low risk	0.1
$15 \leq y < 30$	Medium risk	1
$30 \leq y < 50$	High risk	10
$50 \leq y$	Very high risk	100

is assigned a quantitative social impact factor. Following the previous example, the unit process with a qualitative level “low risk” is assigned a social impact factor of 0.1. It should be noted in Table 14.1 that the impact assessment scheme is set up so that each increase in qualitative risk level causes an increase in quantitative risk factor by a *factor of 10.* Therefore, there is an exponential increase, and the level “very low risk” with a risk factor of 0.01 is ten thousand times less than the level “very high risk” with a risk factor of 100. The final social impact for a given ECOINVENT process (defined in terms of a reference flow and accompanying functional unit) is then calculated as the product between the worker-hours for that process’s reference flow and the quantitative social impact factor for that process. Reasoning about the setting of the scales for qualitative risk levels and the values for the quantitative social impact factors are presented further in the PSILCA manual (Ciroth and Eisfeldt 2016).

14.2.2 Establishing the Life Cycle Model for Social Assessment

Starting points for the assessment follow those of the environmental assessment. In line with the goal of the study, the four temporal cases considered in the social assessment are as those used for the environmental assessment, namely the base year (2014), the year 2050 according to the REFLEX Mod-RES scenario (hereafter 2050 Mod-RES), the year 2050 according to the REFLEX High-RES centralized scenario (hereafter 2050 High-RES centralized scenario) and finally the year 2050 according to the REFLEX decentralized High-RES scenario (hereafter 2050 High-RES decentralized scenario). For each temporal case the quantity of 1 kWh of grid electricity production is studied.

For each temporal case it is thus intended to assess EU electricity production from a social life cycle perspective. The electricity system as considered includes all capital and consumed material from the stage of raw material extraction up to the final production of electricity for delivery to the grid. For capital goods, only dismantling, demolition and disposal processes are considered for the end-of-life stage. No credits are considered for any potential recycling of capital materials.

Data on total electricity generation disaggregated by generation technology for each temporal case is taken from the REFLEX model ELTRAMOD (cf. Chapter 10). In order to reduce data quantities, a cut-off requirement was set that only generation technologies contributing to over 1% of total generation in any given temporal case was considered. It should be noted that after applying this cut-off criteria, over 99% of total generation was included in the system in all temporal cases.

Starting from the ELTRAMOD data for electricity generation, the life cycle inventory is developed for one unit of electricity production for each generation technology in each temporal case. A process flow diagram in Fig. 14.1 shows the

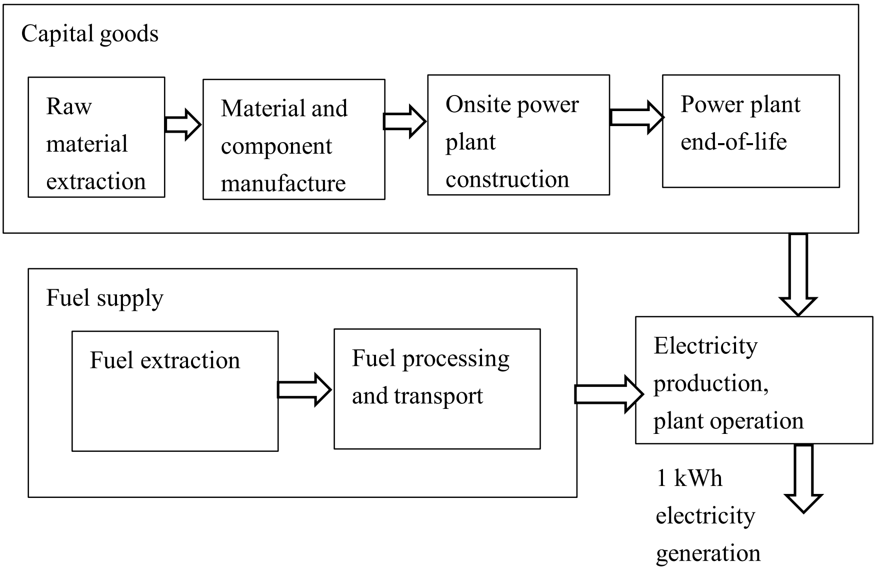

Fig. 14.1 Generic process flow diagram for social life cycle inventory for generation of 1 kWh electricity with a specific generation technology (*Source* Own illustration)

generic process stages included when gathering inventory. Where available, background data is taken from relevant ECOINVENT processes for electricity generation in Germany. This is because electricity generation in ECOINVENT is generally modeled for specific countries and there are many different generation technologies in the database modeled for German conditions. For example, for electricity generation with natural gas combined cycle gas turbine, the background process is taken to be "electricity production, natural gas, combined cycle power plant | electricity, high voltage | cut-off, U—DE". Such processes cover all of the stages shown in Fig. 14.1. However, this approach provides a sound generic starting point for the assessment. It is necessary to develop system specific data for the models used, as described further below.

14.2.2.1 Capital Goods

In general, activity variables and social risk profile for capital goods production for each generation technology are based on the background ECOINVENT processes used to model each generation technology, and they are kept constant for all temporal cases.

However costs for wind (onshore and offshore) and photovoltaic (ground mounted and rooftop) power plants are currently changing rapidly (cf. Chapter 4 and e.g. Louwen et al. 2018). Therefore, activity variables connected to the entire "capital goods" processes for wind power and photovoltaic technologies in the assessment are

Table 14.2 Sector and geographical region for social risk profiles for “onsite power plant production” and “electricity production, plant operation”. Table according to United Nations (2008) and ECOINVENT Centre (2015)

Production stage	Economic sector	Geographical region
Onsite power plant construction	4220a: Construction of utility projects for electricity production, except for liquid fuels	Europe (abbreviated to RER in ECOINVENT)
Electricity production, plant operation	3510: Electric power generation, transmission and distribution	ENTSO-E (the European transmission grid)

changed for the current case compared to the background ECOINVENT processes according to recent capital investment data for each technology (IRENA 2018a; IRENA 2018b; Louwen et al. 2018). Furthermore, since costs for these technologies are further expected to decrease significantly up to 2050, updated activity variables are calculated for the 2050 scenarios using a learning curve approach based on an estimated global installed capacity for each technology (Brown et al. 2019).

A specific process is developed to model “onsite power plant construction” according to average European conditions (cf. Table 14.2). This is done since it is considered that the German conditions used for each background process are not sufficiently representative for the European case. Table 14.2 also shows the specific sector which this process is assumed to belong to. Other than the inputs noted above, inventory data is used directly from the selected ECOINVENT background process.

14.2.2.2 Fuel Supply

For coal and gas-based generation technologies, the countries of origin for respective fuels (i.e. “fuel supply” in Fig. 14.1) are modeled in the base year according to data for supply to the entire EU according to Eurostat (2019). For nuclear generation, the generic global fuel supply considered in the background ECOINVENT process is used for the current case. This is considered relevant in light of the global nature of nuclear fuel supply to the EU—from Canada, Russia, Kazakhstan, Niger and Australia (World Nuclear Association 2019). Meanwhile, for biomass-based generation a mixture of EU-sourced wood chips and globally sourced wood pellets are assumed in the current year.

It is also assumed that the countries of origin for these fuels are the same in the 2050 scenarios as for the current case. This is considered reasonable considering the significant uncertainty in the future development of countries of origin.

Other than the inputs noted above, inventory data is used directly from the selected ECOINVENT background process. Of course, countries of origin may (or will most likely) change until 2050, however, due to the lack of knowledge with regard to the contribution of the countries of origin, the assumption to use todays countries of origin is still the best guess.

14.2.2.3 Electricity Production and Plant Operation

A process is also specifically developed to model "electricity production, plant operation" according to European conditions. The economic sector and geographical region according to ECOINVENT to model this process are shown in Table 14.2. The activity variable (i.e. number of worker-hours) for this stage is calculated based on the labor intensity of the specific sector and geographical location shown in Table 14.2 and generic cost data in ECOINVENT for the specific technology in question. Note that this is done for all generation technologies considered.

14.2.3 Social Impact Categories

The assessment focuses on the stakeholder category workers since this is judged to be a category directly connected to and affected by supply chains for electricity production. From the indicators available to assess the worker stakeholder category, 12 are selected as shown in Table 14.3 below. Table 14.3 also shows how the selected indicators are related to the UN Sustainable Development Goal 8 Decent work and economic growth.

14.2.4 Calculation Method

Firstly, the total quantity of worker-hours for 1 kWh of electricity generation for each generation technology in each temporal case is calculated using the LCA software tool open LCA. These data are extracted to excel. This gave the pure activity variable for production by each technology. The quantity of worker-hours required for a given generation technology in a given temporal case is then calculated as:

$$X_{T,Y} = x_{T,Y}.P_{T,Y} \tag{14.1}$$

where $X_{T,Y}$ is the total number of worker-hours due to generation technology T in temporal case Y, $x_{T,Y}$ is the number of work hours required to generate 1 kWh of electricity with generation technology T in scenario Y and $P_{T,Y}$ is the quantity of electricity generated in with technology T in temporal case Y in kWh. The total amount of worker-hours required for electricity generation for all n generation technologies in a given temporal case $X_{Tot,Y}$ can then be calculated as:

$$X_{Tot,Y} = \sum_{T=1}^{n} X_{T,Y} \tag{14.2}$$

Table 14.3 Subcategories and indicators for social risk used in this assessment, also showing the connection to UN Sustainable Development Goal 8 Decent work and economic growth

Subcategory	Indicators	Connection to UN Sustainable Development Goal 8 Decent work and economic growth
Forced labor	Frequency of forced labor	**8.7** Take immediate and effective measures to eradicate forced labor, end modern slavery and human trafficking and secure the prohibition and elimination of the worst forms of child labor, including recruitment and use of child soldiers, and by 2025 end child labor in all its forms
	Trafficking in persons	
Child labor	Child labor, total	
Health and safety	DALYs due to indoor and outdoor air and water pollution	**8.8** Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment
	Non-fatal accidents	
	Safety measures	
Workers' rights	Right of association (Yes/No)	
	Right of collective bargaining (Yes/No)	
	Right to strike (Yes/No)	
Fair salary	Living wage, per month	**8.5** By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value
	Minimum wage, per month	
	Sector average wage, per month	

Secondly, the *social impact* for 1 kWh of electricity production for each generation technology in each temporal case is calculated in openLCA and extracted to excel. See the earlier Sect. 14.2.1 called "Background to the SOCA add-on for social LCA" for how this latter step is performed. The indicators and subcategories for which social impacts are calculated are given in Table 14.3. The calculation of the social impact due to electricity generation for a specific technology in a given temporal case is performed according to the method summarized by Eq. 14.1. The calculation of the total social impact due to electricity generation in a given temporal case then follows the format shown in Eq. 14.2.

Quantitative social impact factors (according to the scale shown in the right hand column in Table 14.1) for each temporal case and for each social subcategory considered is then calculated as the social impact calculated in the subcategory (see paragraph above) divided by the amount of worker-hours (see earlier in the Sect. 14.2.4 and Eq. 14.2).

14.2.5 Contribution Analysis

The first step in the contribution analysis is to identify the electricity generation technologies making a *significant contribution* to any social risk subcategory considered in any the temporal case. This group included coal generation (in the base year only), natural gas-based technologies (in all temporal cases, mainly combined cycle gas turbine with and without carbon capture and storage technology), nuclear generation (mainly in the base year), wind power (mainly in 2050 High-RES scenarios) and solar power (mainly in 2050 High-RES scenarios).

The second step in the contribution analysis is to assess the percentage-wise contribution of different parts of the supply chain (according to the process flow diagram shown in Fig. 14.1) for each generation technology using the contribution tree function in openLCA. Finally, all unit processes in the supply chain for a given generation technology are arranged in descending order of their social impact contribution for each subcategory. According to this analysis, specific regions (or countries) and sectors making significant contributions to social impacts in each temporal case could be identified.

14.3 Results

Figures 14.2, 14.3 and 14.4 shows results from the social assessment of electricity production in the EU. Comparing Fig. 14.2 with Fig. 14.3 it can be deduced that increased labor intensity (by about 10% comparing High-RES decentralized scenario with the current case) is responsible for a certain portion of the increase in social impacts seen in Fig. 14.2. Having said that, the large increase in calculated impacts seen in for example fair salary or forced labor show that an increase in risk levels (cf. Table 14.1) is also responsible for the observed increase in social impacts. The contribution analysis shows that the increases in social impacts in future scenarios observed in Fig. 14.2 (for all impact subcategories except for health and safety) is due to the increasing share of gas-based generation in the future. Gas technologies have higher than average impact considered per unit electricity generation.

As shown in Fig. 14.2, the largest contributors to impacts across the board in the current case (2014) are fossil-based generation technologies and nuclear power. One significant reason for the large impacts from coal and nuclear power is that they constitute large shares of the total generation in Europe in the current case—22 and 28%, respectively. Gas represents a smaller share of the production mix, only 6% but contributes to impacts because of relatively high impacts per unit electricity generation. Contribution analysis shows that for gas generation, it is "fuel supply" (according to the process flow diagram in Fig. 14.1) that is responsible for over 90% of total impacts. For coal generation, "fuel supply" also dominates and is responsible for between 75 and 85% of total impacts depending on the impact category.

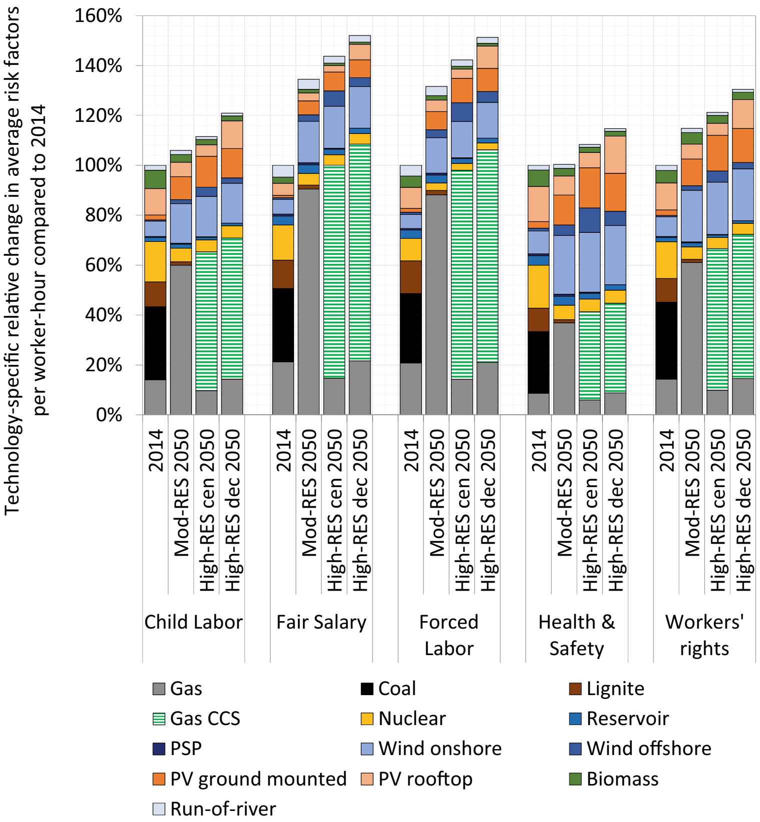

Fig. 14.2 Calculated social impacts per unit electricity generation in the EU-27, Norway, Switzerland, United Kingdom and Balkan countries for all subcategories and temporal cases considered. Impacts are normalized to calculated impact in the 2014 base year. Abbreviations: PSP—pumped storage plant, CCS—carbon capture and storage, PV—photovoltaic. For total electricity generation in scenarios please see Chapter 10 (*Source* Own illustration)

For nuclear technology, fuel supply answers for between 42 and 74% of total impacts depending on the impact category. In the subcategory fair salary, the process "Electricity production, plant operation" (cf. Figure 14.1) contributes 43% of the total impact for nuclear power. Solar power and wind power make more modest contributions in all impact categories in the current case. Impacts per unit of electricity for wind generation technologies are close to the average across all generation technologies. For wind power onshore,[1] the process "capital goods" (see flow diagram, Fig. 14.1) contributes over 90% of the total impact from the technology for all subcategories with the exception of fair salary, where the impact from "capital

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[1] Chosen for contribution analysis because it dominates the wind power category in terms of share of total generation and in observed social impacts. Largely similar contributions are observed for offshore wind power.

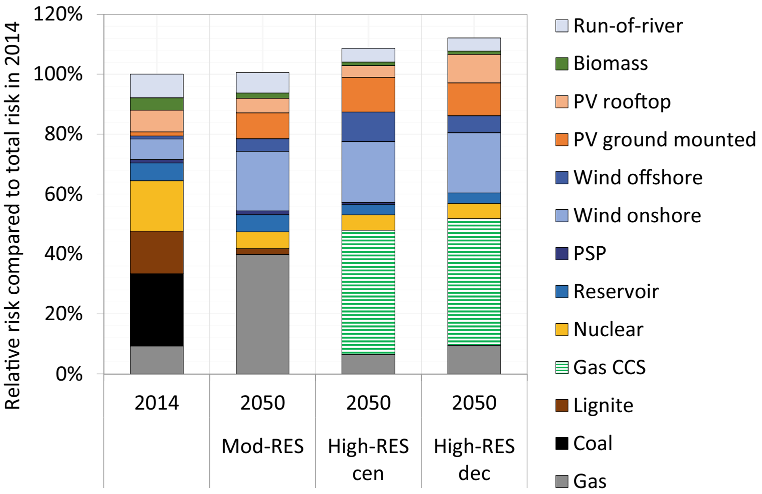

Fig. 14.3 Calculated worker-hours per unit electricity generation in the EU-27, Norway, Switzerland, United Kingdom and Balkan countries for all subcategories and temporal cases considered. The values are normalized to the calculated worker-hours in the 2014 base year (*Source* Own illustration)

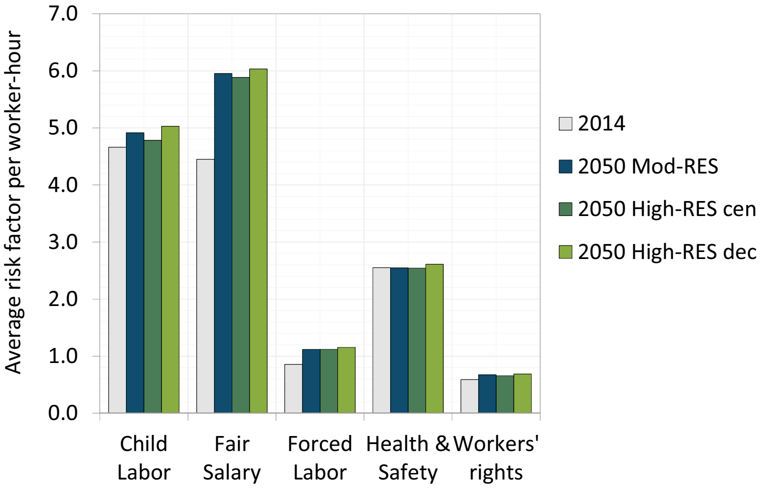

Fig. 14.4 Average social impact factor per unit electricity generation in the EU-27, Norway, Switzerland, United Kingdom and Balkan countries for all subcategories and temporal cases considered. The values on the y-axis are comparable to the quantitative social impact factors given in Table 14.1

goods" amounts to 66%. In this category, the process "Electricity production, plant operation" (cf. Fig. 14.1) contributes 30% of the total impact. In the current case, solar power (all types) contributes only 3% of the total generation, so the impacts arise because solar power has impacts per unit electricity generation that are significantly higher than average across all impact categories. The processes "raw material extraction" and "material and component manufacture" (see flow diagram, Fig. 14.1, i.e. the production of panels and mounting systems and raw material production required) together account for between 70 and 98% of total impacts per unit generation for rooftop solar[2] depending on the impact subcategory.

In all future cases, gas-based generation technologies dominate in all impact categories. This is because the share of gas-based technologies in total generation increases to around 30% in all scenarios, combined with the fact that for all impact subcategories except for health and safety, gas technologies have higher than average impact considered per unit electricity generation. This is the case in spite of an assumed small increase in generation efficiency for gas technologies. Coal and lignite based generation have been largely eliminated from the mix in all 2050 scenarios. Wind power meanwhile increases its share of total generation to around a third in each 2050 scenario, leading to the increases in wind power's share of total impacts shown in Fig. 14.2. The share of impacts is nevertheless mitigated by the fact that the cost for capital goods (i.e. the wind power plant itself and necessary grid connection) reduced by about a third for each wind power technology, causing the specific impact per unit electricity generation to reduce by about the same amount between the current case and 2050. One interesting feature arising from the contribution analysis for wind power is that in future cases, the production of steel including its supply chain accounts for large proportions of the total impact per unit electricity generation. For example, it amounts to 56% of the total for onshore wind power in the subcategory child labor and 28% in the subcategory health and safety for the same technology. The social impact per unit electricity generation decreases by about two thirds in 2050 scenarios for each solar generation technology thanks to the learning curve approach applied. Nevertheless, due to the increase in PV share in the electricity mix, solar's contribution to social impacts grows up to 2050. The contribution analysis shows that even in 2050 between 48% (for the subcategory fair salary) and 91% (for child labor) of the total contribution due to the ground mounted PV arises due to the processes "raw material extraction" and "material and component manufacture". Similar trends are observed for rooftop PV.

The scale on the y-axis of Fig. 14.4 can meanwhile be compared to the values of the quantitative social impact factors in Table 14.1. The figure shows that on average, for all temporal cases, child labor, fair salary and health and safety have between a medium risk level (a value of 1 on the y-axis) and a high risk level (a value of 10 on the y-axis). Meanwhile, forced labor has on average slightly more than a medium risk level and workers' rights between a medium risk level and a low risk level. If it is accepted that the qualitative performance levels can be reasonably compared

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[2] Chosen for contribution analysis because it dominates the PV rooftop category in impacts in the current case. Similar trends are observed for PV ground mounted plants.

Table 14.4 The proportion of social impacts that are identified to specific countries or geographic regions according to contribution analysis. High-RES centralized scenario was not selected for this analysis

	Current		Mod-RES 2050		High-RES dec 2050	
	Identified with	Not identified with	Identified with	Not identified with	Identified with	Not identified with
	Geographic specificity					
Child labor	0%	100%	0%	100%	0%	100%
Fair salary	41%	59%	58%	42%	62%	38%
Forced labor	27%	73%	49%	51%	50%	50%
Health and safety	12%	88%	11%	89%	11%	89%
Workers' rights	8%	92%	2%	98%	2%	98%

between impact subcategories (i.e. a medium risk in for example "fair salary" can be compared with a medium risk in "child labor") then Fig. 14.4 establishes a clear prioritization of which social performance categories should be addressed in order to improve the performance. On the other hand, considered from an ethical perspective it is problematic to objectively compare risk in this way, and it is at least an issue that should be left to the decision-maker (see discussion in Ciroth and Eisfeldt 2016).

Table 14.4 shows the breakdown of calculated social impacts between those that could be assigned to a specific geographic location (country or region) according to the modeling approach used and those that are calculated according to non-geographically specific (e.g. global or rest-of-world) average social performance values according to the modeling approach. The main observation is that a large proportion of social impacts for the subcategories considered are calculated according to non-geographically specific average values and therefore provide weak support for decisions for improved social performance. For example, as good as all impact in the child labor subcategory occurs due to non-geographically specific processes in all temporal cases (cf. Table 14.4). The geographic specificity of calculated impacts for workers' rights is only 2% in future scenarios and therefore not considered further in this analysis (cf. Table 14.4).

Table 14.4 also shows that for forced labor and fair salary in particular, geographically specific processes are identified as making significant contributions in all temporal cases shown. A major cause here is fuel supply from Russia. In the current case these impacts amount to 23% of the total assessed impact in the category, with 12% arising from the sourcing of natural gas from Russia, 12% from the sourcing of coal in the country and 3% from nuclear fuel cycle-related activities. Meanwhile, for the future cases (where High-RES decentralized is the case analyzed), as much as 42% of the total risk in the category can be attributed to Russia, all due to the natural gas supply chain from the country. That the proportion due to Russia increases between the current case and the future scenarios is due to the increase in the proportion of gas-based generation, which occurs for all future scenarios. Russian gas production is further assigned a level of "high risk" for the indicator for "trafficking in persons". According to source data for the indicator (U.S. Department of State 2014) this is because the country is one of few with a tier 3 designation, meaning that it is judged not to be making significant efforts to comply with the minimum standards in the Trafficking Victims' Protection Act (TVPA) (U.S. Department of State 2008).[3] There are meanwhile small contributions in the forced labor category from certain activities geographically specific to Europe, up to 8% of the total in future scenarios. Data sources used for the risk assessment in the category (International Labour Organization 2012; U.S. Department of State 2014) and other relevant sources (Walk Free Foundation 2018) suggest that the occurrence of forced labor particularly in the Eastern and Southern peripheries of the EU (although it is judged to occur to some extent in all parts of the EU) and the lack of complete application of the Trafficking Victims' Protection Act (TVPA) (U.S. Department of State 2008) in certain EU countries causes this. The judged risk level for forced labor geographically specific to Europe is only medium. However, a large proportion of the total worker-hours for in particular wind power are specific to Europe, causing the processes to feature as non-negligible in this analysis.

About 20% of the total calculated impacts for fair salary in the current case arise due to coal and natural gas supply from Russia. Meanwhile source data in the category fair salary (Guzi and Kahanec 2018) demonstrates that the reason that processes geographically specific to Russia (in particular in the natural gas supply chain) play such a large role is the fact that the estimated living wage in the country is above the lowest estimated level for a minimum wage in the country (cf. Guzi and Kahanec 2018 for more information about how living wage is evaluated). A smaller, though non-negligible proportion of social impacts in fair salary also arise due to the power production process across the different generation technologies and for onsite plant construction for wind power and solar power, performed according to European average conditions. This arises largely because the living wage is relatively high in the European geographic designation. The major increase in total impact (cf. Figure 14.2) and in geographic specificity between the current case and the future scenarios for fair salary is due to the increased demand for gas from Russia, mitigated somewhat by the elimination of social impact from coal due to the fact that it is not used in any future scenario.

Considering health and safety, only 12% of the total impact in the category can be identified with any geographic specificity in the current case. Breaking this down further, the geographically specific impacts can be localized to coal mine operation in Columbia and North America (specifically a very high risk of non-fatal accidents), nuclear fuel production in Russia and Europe (due to very high risk of lack of sufficient safety measures) and for onsite construction of wind power plants at European average conditions (high risk of non-fatal accidents). Geographic specificity for impacts remains at just over 10% in all future scenarios, but arises principally as a

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[3] However, this appraisal may change dependent on actions taken (or even not).

result of onsite construction of wind power plants under European average conditions due to increase in the significance of wind power in the energy mix and the decrease in nuclear and coal generation over the same period.

14.4 Concluding Discussion and Policy Implications

This work has shown that the SOCA add-on can identify geographic locations where improvement in social performance will non-negligibly improve the performance of future energy systems. However in this work it is only possible for a limited number of social impact categories.

Since all indicators assessed in the analysis have been related to the UN SDGs (cf. Table 14.3) SOCA is therefore shown to be useful in demonstrating areas for improvement in consideration of the SDGs. However, the fact that large proportions of the total impacts (in particular for categories such as child labor and workers' rights) could not be assigned a geographically specific location point to ongoing limitations with applying SOCA. A large number of SDGs remain to be addressed by the approach. Also the fact that much of the calculated impact could not be assigned to geographically specific regions implies that SOCA does not facilitate a screening to identify the largest areas of social impact. Indeed, the development of geographically specific processes for major stages for generation technologies that is performed in this study (e.g. for onsite plant construction and power generation, cf. Table 14.2) is a delicate and time-consuming process. Facilitating this in future is therefore a key step in the further development of the SOCA add-on.

Furthermore, though the contribution analysis allows geographically specific potential social impacts to be identified, source data themselves in many cases lack sector specificity. A sustainability report from a large company engaged in gas production and supply in Russia demonstrates that in the industry there is an intention to work actively with salary issues and to apply International Labour Organization standards, including the elimination of forced labor and trafficking in persons (Gazprom 2018). Reporting standards could of course be stricter. Considering the evidence of e.g., lack of implementation of the protocol on trafficking in persons in the country, Russian gas suppliers could provide further evidence of initiatives to track and eliminate such violations affecting their own organizations. The issue could on the other hand be addressed on a diplomatic and political level through the implementation of the Trafficking Victims' Protection Act (U.S. Department of State 2008) in Russia, as well as comprehensively in European nations.

Considering the issue of fair salary arising in Russian fuel supply and in electricity production according to European conditions, beyond general salary-related policies, statistics could be produced to track the relationship between salaries in relevant industries (gas supply in Russia and electricity production in Europe) and relevant measures of living wage and minimum wage in the respective geographic locations.

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Chapter 15
Spatially Disaggregated Impact Pathway Analysis of Direct Particulate Matter Emissions

Janusz Zyśk, Artur Wyrwa, and Beata Sliz-Szkliniarz

Abstract This chapter focuses on the evaluation of air quality and health impacts associated with direct emissions of air pollutants for different REFLEX scenarios based on the Driver-Pressure-State-Impact-Response framework. Ambient concentration of air pollutants is calculated with the use of the Polyphemus Air Quality System. Health impacts are calculated using the concentration-response functions. Results show that particulate matter emissions in Europe will decrease by 10 times till 2050. Also ambient pollutants concentrations decrease in 2050 in all REFLEX scenarios. This leads to the reduction of external costs of almost 20 billion EUR per year.

15.1 Introduction

This study focuses on the evaluation of air quality and health impacts that are associated with direct emissions of air pollutants in the EU-27, Norway, Switzerland and United Kingdom. Direct emissions result mainly from the combustion of fossil fuels during the operational phase of energy technologies. The subject is of great importance for EU citizens as air pollution leads to significant damage to human health, environment, buildings and other materials. Exposure of humans to elevated concentrations of air pollutants increases morbidity leads to premature mortality and shortening the life expectancy (WHO 2018; EEA 2016). The contribution of different economic sectors to primary emissions depends on the pollutant considered. For instance, the residential sector was the largest contributor to particulate matter emissions in 2018, contributing to 47% and 61% of total PM_{10} and $PM_{2.5}$ emission in EU-27 Norway, Switzerland and United Kingdom, respectively (EMEP 2018). In the same year, the energy production and distribution sector was the largest

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contributor to total SO_2 and road transport to NO_x emissions. There is no doubt that progress has been made in EU in the last twenty years in reducing emissions of the main air pollutants due to implementation of relevant legislation (e.g. Directive EU 2010). Substantial emission reduction of pollutants such as $PM_{2.5}$, PM_{10}, SO_x, NO_x, NMVOCs (Non-methane volatile organic compounds) has been achieved in particular in the energy production and distribution as well as in road transport sectors. Still, however, in many regions of the European Union, the current limits on ambient pollutant concentrations are often exceeded (EEA 2016). Estimations show that even 24%, 30%, 19% of urban population in the EU-27, Norway, Switzerland and United Kingdom is exposed to B(a)P (Benzo(a)pyren), O_3 and PM_{10} concentrations, respectively, that are above the EU reference values (EEA 2016; Directive EU 2008).

This study, following the DPSIR (Driver-Pressure-State-Impact-Response) framework (Guariso and Volta 2017), assesses how the implementation of energy scenarios elaborated within the REFLEX project would impact the future air quality, residents' health and external costs. The air quality modeling system Polyphemus is used to analyze the changes in future ambient pollutants concentration. Then, using the data on population density distribution and results of epidemiological studies the health impacts of air pollution are estimated. Finally, the monetary valuation of health damages is carried out and the values of the so- called external costs associated with different energy scenarios are compared.

15.2 Description of the Method

The approach to calculate the external costs of direct pollutant emissions is based on the Driver-Pressure-State-Impact-Response (DPSIR) framework depicted in Fig. 15.1 (Wyrwa 2015). Based on the chain of causality human caused drivers (use of primary energy sources) are linked to pressures on the environment (emissions),

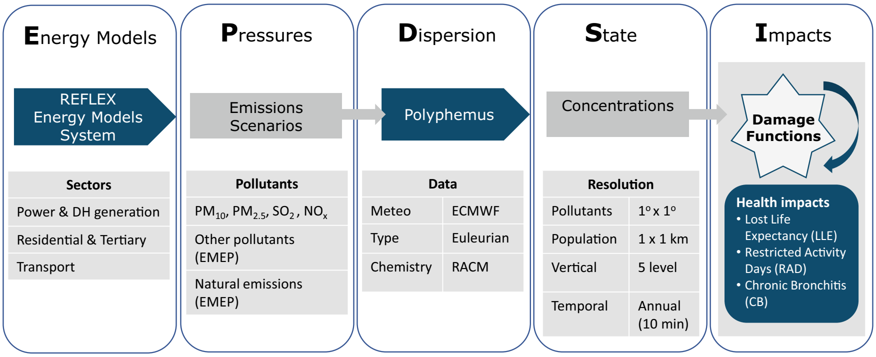

Fig. 15.1 The steps of analysis of external costs of direct emissions. (*Source* Own illustration)

changes of environmental states (air quality, human health) and eventually responses to correct the situation (constraints imposed on energy scenarios). “Drivers”, “Pressures” and “Responses” are addressed with the “REFLEX energy models system”, whereas “States”, including the level of ambient air concentration and deposition of pollutants, were covered by Polyphemus - a full system for air quality modeling. Analysis of the health impact is limited to people’s long-term exposure to fine particulate air pollution.

15.2.1 Emission Scenarios

Emissions scenarios are prepared based on the results of the ELTRAMOD, TIMES-Heat-EU, ASTRA and FORECAST models for different REFLEX scenarios. All REFLEX energy models provide results on CO_2 emissions. However, they lack information on emissions of air pollutants, such as SO_2, NO_x, PM_s which need to be taken into account in air quality modeling. The results of these models as regards to electricity, district heat generation or final fuel consumption (so called activity) are used together with the relevant emission factors for different pollutants to derive the emission scenarios. The emission factors for ELTRAMOD are taken from the ECOINVENT database and modified according to efficiency improvements of power generation technologies assumed in the ELTRAMOD model. The emission factors for TIMES-Heat-EU are extracted from the GAINS model (GAINS 2019). In case of the FORECAST model, the results on final fuel consumption in the residential and tertiary sectors are used together with emission factors for combustion installations meeting the current Ecodesign limits (Commission Regulation [EU] 2015). With reference to the transport sector, the results of the ASTRA model in terms of Tank-to-Wheel yearly emissions are provided by TRT[1]. Emissions are related to land modes (road, rail, inland waterways) for both passenger and freight transport demand, as well as air passenger mode and freight maritime ship mode. Emissions from air mode are treated by separating the contribution of the LTO cycle (landing and take-off) and the cruise phase, because the vertical level of these emissions is different (they are released at different heights what influence their atmospheric dispersion).

The air quality model requires information also on natural and anthropogenic emissions. The REFLEX energy system models, however, do not cover all the economic sectors that generate emissions. Therefore, the missing dataset is complemented with emission inventories of the European Monitoring and Evaluation Programme (EMEP 2018). There are two simulation cases considered for anthropogenic emissions: (i) historical emissions reported to EMEP for 2015, and (ii) REFLEX emissions (all scenarios) for 2050 for power and district heat sector, road transport, households and tertiary (remaining emissions were again complemented with the EMEP data). The REFLEX emissions are distributed horizontally based on the EMEP emission data for 2015. Table 15.1 shows the emissions of pollutants in

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[1] TRT Trasporti e Territorio: responsible project partner for transport modeling.

Table 15.1 Total PM_{10} emissions in 2015 and in 2050 (Mod-RES) [Mg]

	Sector					
	Residential & Tertiary		Road Transport		Power & District Heat Generation	
Year	2015	2050	2015	2050	2015	2050
country						
AT	8,451	549	3,914	1,358	1,056	353
BE	13,281	510	5,455	1,983	416	239
BG	25,055	137	3,383	521	1,372	38
CH	2,,467	707	3,304	1,015	70	11
CY	82	29	496	41	323	8
CZ	30,449	664	3,902	1,200	2,297	180
DE	22,148	6,040	29,571	11,328	9,304	913
DK	14,954	296	2,505	618	446	135
EE	2,722	79	538	117	4016	832
ES	55,023	1,267	15,178	6,599	6,498	131
FI	11,360	360	7,845	880	1,268	313
FR	72,700	2,550	34,690	11,578	2,138	593
GR	10,967	301	4,564	804	10,070	12
HR	16,051	189	1,908	404	525	25
HU	47,430	868	3,454	769	339	84
IE	7,706	218	2,717	822	676	70
IT	111,733	2,031	26,233	7,804	770	534
LT	3,840	201	1,310	275	195	50
LU	526	29	897	184	34	23
LV	9,688	128	898	183	1,935	36
MT	0	4	1,032	18	265	23
NL	2,149	825	4,876	1,512	368	372
NO	16,753	234	2,630	854	1,244	0
PL	110,409	2,679	11,064	4,961	20,715	424
PT	16,539	393	4,958	1,078	428	92
RO	92,178	1,005	5,148	954	5,335	50
SE	5,826	482	16,320	1,075	1,213	211
SI	8,902	65	1,208	441	363	32
SK	28,106	183	1,685	622	564	70
UK	45,901	2,997	21,802	7,306	5,026	219
Total	793,396	26,022	223,487	67,304	79,270	6,075

Source Own illustration

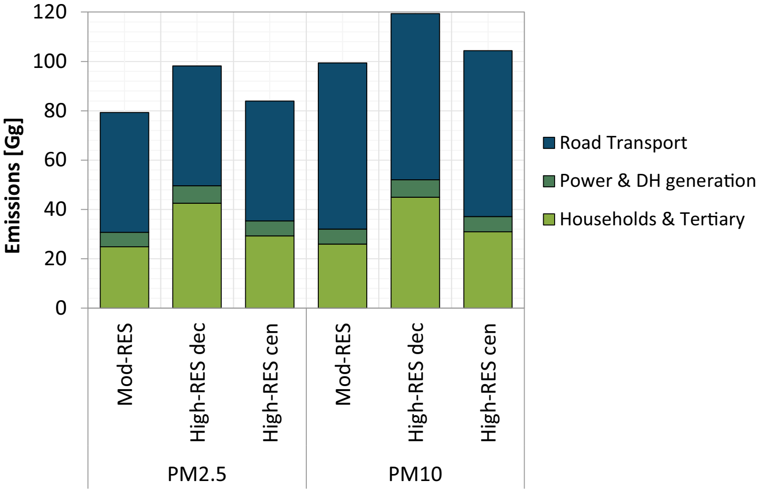

Fig. 15.2 Emissions of PM_{10} and $PM_{2.5}$ in 2050 for different REFLEX scenarios. (*Source* Own illustration)

2015 and 2050 from the power and district heat sector, road transport, residential and tertiary sector that are used as an input to the air quality modeling.

Total PM_{10} emissions in 2015 from all the sectors and countries presented in Table 15.1 equaled to approx. 1 million ton. Figure 15.2 shows particulate matter emissions for different REFLEX scenarios in 2050.

According to the scenarios PM emissions in the sectors listed in Table 15.1 are reduced by 10 times until 2050. In all REFLEX scenarios the climate-oriented goals strongly support the development of renewable energy sources. The most significant reduction is observed for the residential and tertiary sector where the fuel and technology switch take place. Particularly, high reductions occur in 2050 in Eastern European countries such as Poland, Bulgaria, which are now struggling with large emissions from the residential sector (Table 15.1). The difference in results between the REFLEX scenarios is relatively small (Fig. 15.2). A larger difference occurs in the residential and tertiary sector than in the power and district heating sector. It is mainly due to the different structural use of solid biomass for heating. Figure 15.3 shows the solid biomass consumption for different sectors according to the results of the REFLEX energy models. In fact, biomass is covering a significant proportion of the EU's heat demand at present (EEA 2016) and in the REFLEX scenarios it maintains to play an important role in the future.

Figure 15.3 indicates that in the High-RES decentralized scenario $PM_{2.5}$ emissions are higher than in the High-RES centralized case. The main reason is that in the former, more biomass is directly used by households for heating (in installations meeting the Ecodesign emission standards). In the latter, more biomass is used in CHPs, for which stricter emission standards are assumed. Hence, the use of biomass as residential fuel is on one hand leading to reduction of CO_2 emissions but on the

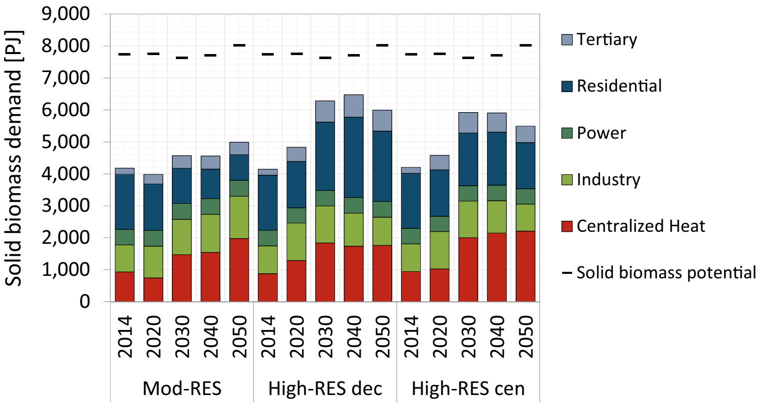

Fig. 15.3 Solid biomass consumption for different sectors according to the results of the REFLEX energy models [PJ]. (*Source* Own illustration)

other is causing higher $PM_{2.5}$ emissions from this sector due to less strict emission standards for residential heating.

15.2.2 Air Quality Modeling

Ambient concentration of air pollutants is calculated with the use of the Polyphemus Air Quality System for each REFLEX emissions scenario. Polyphemus is a complex modeling system for air quality (Mallet et al. 2007; Zyśk et al. 2015). It contains two types of dispersion models: Gaussian and Eulerian. In this modeling exercise an Eulerian chemistry-transport-model called Polair3D is used for both gaseous and aerosol species. Polair3D tracks multiphase chemistry: (i) gas, (ii) water and (iii) aerosols. The transport driven by wind is approached with the third order direct space time (DST3) and the piecewise parabolic method (PPM). Gas-phase chemical scheme is RACM (also other chemical schemes e.g. CB05, RADM 2, Melchior) are available. Aerosol chemistry is treated depending on the cloud liquid water content. Inside clouds, aqueous-phase chemical reactions are modeled using the Variable Size-Resolution Model (VSRM). Outside clouds, a size-resolved aerosol model (SIREAM) treats the effects of condensation/evaporation, coagulation and nucleation upon the particle size distribution. The ISORROPIA module is used for inorganic aerosol thermodynamics.

The main equation for the chemistry-transport that Polair3D solves numerically includes three terms: (i) advection (transport driven by wind), (ii) diffusion (mainly turbulent mixing in the vertical layer) and (iii) chemistry (chemical production as well as dry and wet deposition) (Boutahar et al. 2004).

Running Polyphemus requires, inter alia, preparation of external databases, such as meteorological fields, emission databases, land use coverage (and miscellaneous data associated with land categories), pollutant concentrations at higher scales (e.g. global concentrations, which constitute the boundary conditions for continental simulations), and physical parameters associated with chemical species. The meteorological parameters are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological data for 2008. The ECMWF data are provided with a geographical resolution of 0.25° on 54 vertical levels every 3 h. Running the simulation requires also: (i) calculation of biological and sea salt emission, (ii) preparation of the ground emissions, (iii) generation of the meteorological fields, (iv) generation of the initial and boundary conditions, (v) calculation of the dry deposition velocity.

The analysis is performed for a domain covering Europe with the geographical extend of 12.0°W, 27°E of longitude and 35.0°N–69°N of latitude. This mesh consists of 40 × 34 cells with a horizontal resolution of 1.0° × 1.0° (along longitude and latitude respectively. Five vertical levels are used with the following limits [in meters above surface]: 0, 50, 600, 1,200, 2,000, 3,000. Setting the simulation is run with the time step of 10 min and results are saved each 1 h.

15.2.3 Health Impacts and External Costs

Over the last decades, many studies have been carried out on the health impacts of human exposure to elevated concentrations of air pollutants (both short and long-term). These include, inter alias, observational and experimental human studies, animal studies and in vitro studies (Bickel and Friedrich 2005). In one of the most well-known research papers described in the literature, Pope et al. (2002) analyze the relationship between long-term exposure to fine particulate air pollution and find that each 10-mg/m^3 elevation in fine particulate air pollution is associated with approximately 6% increased mortality. The results of the studies show that air pollution aggravates human's morbidity (especially respiratory and cardiovascular diseases) and leads to premature death i.e., deaths that occur before a person reaches an expected age (WHO 2018; EEA 2018).

The approach to estimate the health impacts of air pollution applied in this study is largely based on the methodology developed within a series of the ExternE projects (European Commission 1999). According to ExternE, fine particulate matter with an aerodynamic diameter of 2.5 mm or less (primary and airborne), is responsible for the most significant impacts to human health. Health impacts considered in this study are limited to people's long-term exposure to fine particulate ($PM_{2.5}$) air pollution. The prevailing health damages caused by PMs are: loss life expectancy, chronic bronchitis and restricted activity days (Rabl and Spadaro 2008). Loss of Life Expectancy (LLE) is an indicator often used as a proxy for quantifying the overall impact on a population's health. It is found suitable for the comparative analysis of energy scenarios (Amann et al. 2011). It is expressed in the years of life lost (YOLLs) being an estimate of the average years that a person would have lived if he or she had not died prematurely. Chronic bronchitis (CB) refers to newly observed cases, but not to change

Table 15.2 Slopes and unit values of considered CRFs for $PM_{2.5}$

CRF function (effects)	CRF [cases μg^{-1} m^{-3}]	Fr [%]	Unit value [EUR_{2013} $case^{-1*}$]
$PM_{2.5}$ - Mortality YOLL	3,42E-04	100	57,510
$PM_{2.5}$ - Chronic Bronchitis	3,90E-05	80	38,578
$PM_{2.5}$ - Restricted Activity Days	4,20E-02	80	98

*Case means: YOLL, RAD, CB

in the prevalence illness rate among adults. Restricted Activity Days (RAD) corresponds to days when an individual's routine activities are disrupted. Health impacts (I) are calculated using the concentration-response functions (CRFs), which relate the quantity of a pollutant that affects a population (accounting for the absorption of the pollutant from the air into the body) to the physical impact (Eq. 15.1).

$$I = Con \cdot Pop \cdot Fr \cdot CRF \tag{15.1}$$

Where: I is the health impact of a given type (i.e. years of life lost – YOLL, restricted activity days –RAD or chronic bronchitis – CB), Con is the concentration of $PM_{2.5}$ [$\mu g/m^3$], Pop denotes the population exposed, Fr is the fraction of population affected and CRF is the concentration-response function for a given impact type. $PM_{2.5}$ impacts have been estimated for the full range of observed concentrations.

In the next step, the monetary values (leading to external costs) are assigned to respective health impacts. In case of loss of life expectancy, the cost of mortality is estimated usually as the willingness-to-pay to avoid the risk of an anonymous premature death. Cost of chronic bronchitis expresses all medical treatment expenses over the patient's lifetime. Restricted activity days takes into account cost of illnesses, loss of productivity and welfare loss.

The monetary values and CRFs used in the study, which have been derived from the results of ExternE (Bickel and Friedrich 2005), vetcen database (Holland and Watkiss 2002) and AQMEII3 initiative (Ulas et al. 2018) are presented in Table 15.2.

In addition to the parameters presented in Table 15.2, information on ambient $PM_{2.5}$ concentrations and demographic data are also required to calculate the health impacts and external costs (Eq. 15.1). Ambient pollutants concentrations are calculated using Polyphemus air quality system. The demographic data are taken from GEOSTAT 2011. This dataset includes population distribution with 1 km × 1 km spatial resolution.

15.3 Results

Following the DPSIR logic at first the results of atmospheric dispersion of PMs are presented. Figure 15.4 shows modeled ambient $PM_{2.5}$ concentration at surface level in

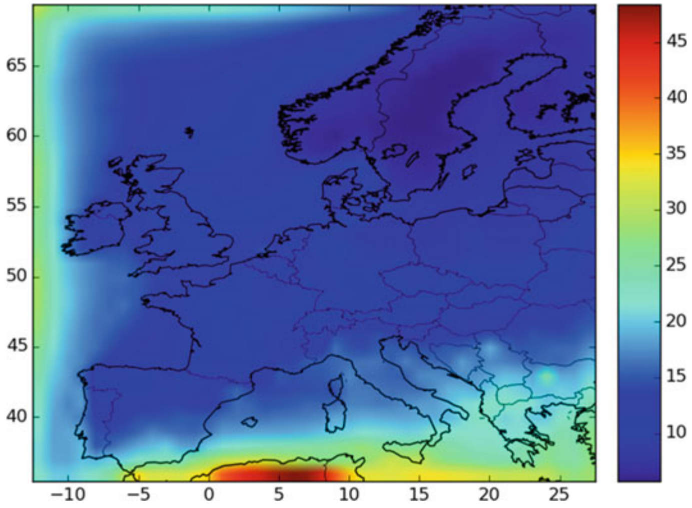

Fig. 15.4 Modeled ambient $PM_{2.5}$ concentration at surface level in 2050 for Mod-RES scenario [μm/m^3]. (*Source* Own illustration)

2050 for the Mod-RES scenario in which, as presented in Fig. 15.2, PM emissions are the lowest. Figure 15.5 shows the change in ambient $PM_{2.5}$ concentrations between 2015 and 2050 for the Mod-RES scenario.

According to the Mod-RES scenario, the average annual ambient concertation of $PM_{2.5}$ in the EU-27, Norway, Switzerland and the United Kingdom will be lower

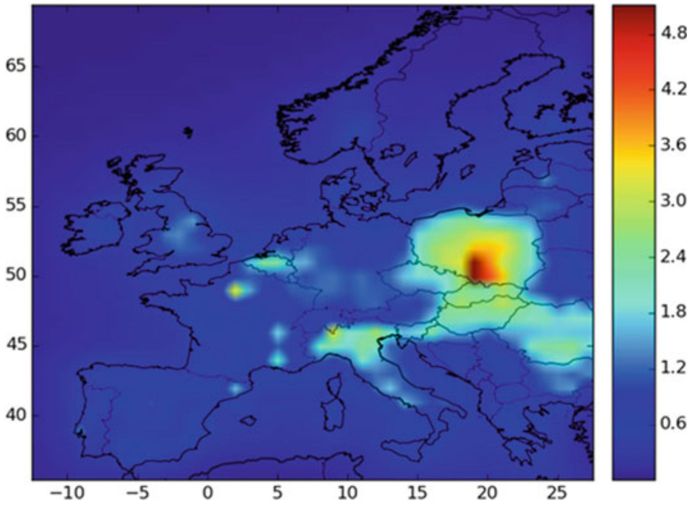

Fig. 15.5 Difference between modeled ambient $PM_{2.5}$ concentration at surface level in 2015 based on EMEP emission data and in 2050 for Mod-RES scenario [μm/m^3]. (*Source* Own illustration)

than 15 $\mu g/m^3$ in 2050. The lowest concertation is observed in Scandinavian countries and highest over Mediterranean countries because of significant share of the natural particulate matter from Sahara (cf. Figure 15.4). The largest reduction in PM_{10} ambient concentrations is observed over Poland (cf. Figure 15.5). This is mainly caused by reduction of emissions form the residential sector. Nowadays in Poland more than 40% of houses and flats use inefficient and highly polluting solid fuel boilers (mainly coal and some biomass) for heating. Reducing the amount of coal burned in this sector and the use of modern boilers meeting the Ecodesign limits will lead to significant improvement of air quality over Poland.

The results of the health impact assessment for 2015 and for the Mod-Res scenario in 2050 are presented in Table 15.3. The health effects are almost the same for the High-RES scenarios due to similar PM emissions and ambient pollutants concentration levels in these scenarios. In total, in the countries presented in Table 15.3 almost 2.2 million YOLL are attributed to $PM_{2.5}$ exposure in 2050.

The results presented in Table 15.3 show that the negative health impact associated with the fine particulate air pollution in 2050 is lower than in 2015 in all the countries. The cumulative number of years of life lost is estimated to be the highest (both in 2015 and 2050) in highly populated countries like Italy, Germany, France, Spain, United Kingdom and Poland. The highest reduction in negative health impacts is observed in Poland (25%), Slovakia (19%), Hungary (16.5%) and Czech Republic (16%). The smallest reduction is observed in Malta and Greece.

Figure 15.6 show the difference between the value of YOLL in 2015 and 2050 (Mod-RES scenario) at the grid-cell level. The greatest reduction in overall value of years of life lost (health benefits) takes place in cells located in Poland, northern Italy, Germany, Romania and United Kingdom. This reduction in YOLL in 2050 corresponds to the modeled decrease in ambient $PM_{2.5}$ concentration over the areas as shown in Fig. 15.6.

The calculated health impacts are used to estimate the value of external costs, which are presented in Table 15.4.

As presented in Table 15.4 the estimated health related external costs attributed to $PM_{2.5}$ exposure for the impact types considered in this study are estimated at about 170 billion EUR per year in 2015. The estimated reduction of external costs according to Mod-RES scenario in 2050 reaches almost 20 billion EUR per year. The significant reduction of PM emissions by 2050 from the sectors considered in this study do not yield a proportional decrease of ambient PM concentration. Hence, also health benefits are moderate. One should bear in mind, that in our study the future emissions from others sector are maintained at a constant 2015 level. The same applies to the boundary conditions that take into account the inflow of PMs emitted outside of the analyzed domain. Moreover, also natural (non-anthropogenic or biogenic) sources, including windblown dust and wildfires contribute to the overall PM problem.

Table 15.3 Health impacts attributable to air pollution of $PM_{2.5}$ in 2015 and 2050 (for the High-RES centralized scenario)

	2015			2050		
Country	YOLL [× 10^3]	RAD [× 10^5]	CB [× 10^2]	YOLL [× 10^3]	RAD [× 10^5]	CB [× 10^2]
AT	35.31	34.69	32.21	31.95	31.39	29.15
BE	54.74	53.78	49.94	46.75	45.93	42.65
BG	46.96	46.14	42.84	44.14	43.36	40.27
CH	33.66	33.07	30.70	30.96	30.42	28.25
CZ	42.32	41.57	38.60	35.52	34.89	32.40
DE	327.12	321.38	298.42	297.22	292.01	271.15
DK	18.38	18.06	16.77	17.19	16.89	15.68
EE	3.53	3.46	3.22	3.33	3.27	3.04
EL	84.66	83.18	77.24	82.09	80.65	74.89
ES	252.60	248.17	230.44	241.27	237.03	220.10
FI	12.45	12.23	11.36	11.80	11.59	10.76
FR	270.22	265.48	246.52	242.68	238.42	221.39
HR	22.94	22.53	20.92	20.66	20.29	18.84
HU	49.04	48.18	44.74	40.96	40.24	37.36
IE	21.34	20.96	19.46	20.60	20.24	18.80
IT	376.38	369.77	343.36	342.16	336.16	312.15
LT	10.04	9.87	9.16	9.00	8.84	8.21
LV	6.29	6.18	5.73	5.59	5.49	5.10
MT	4.82	4.73	4.39	4.78	4.70	4.36
NL	74.43	73.12	67.90	68.77	67.57	62.74
NO	12.90	12.68	11.77	12.21	12.00	11.14
PL	165.31	162.41	150.81	124.50	122.32	113.58
PT	59.26	58.22	54.06	56.14	55.15	51.21
RO	101.66	99.88	92.75	89.63	88.06	81.77
SE	24.23	23.81	22.11	23.11	22.70	21.08
SI	10.02	9.84	9.14	8.79	8.64	8.02
SK	25.19	24.75	22.98	20.42	20.07	18.63
UK	255.30	250.82	232.90	234.30	230.19	213.75
Total	2,401.07	2,358.95	2,190.45	2,166.54	2,128.53	1,976.49

Source Own illustration

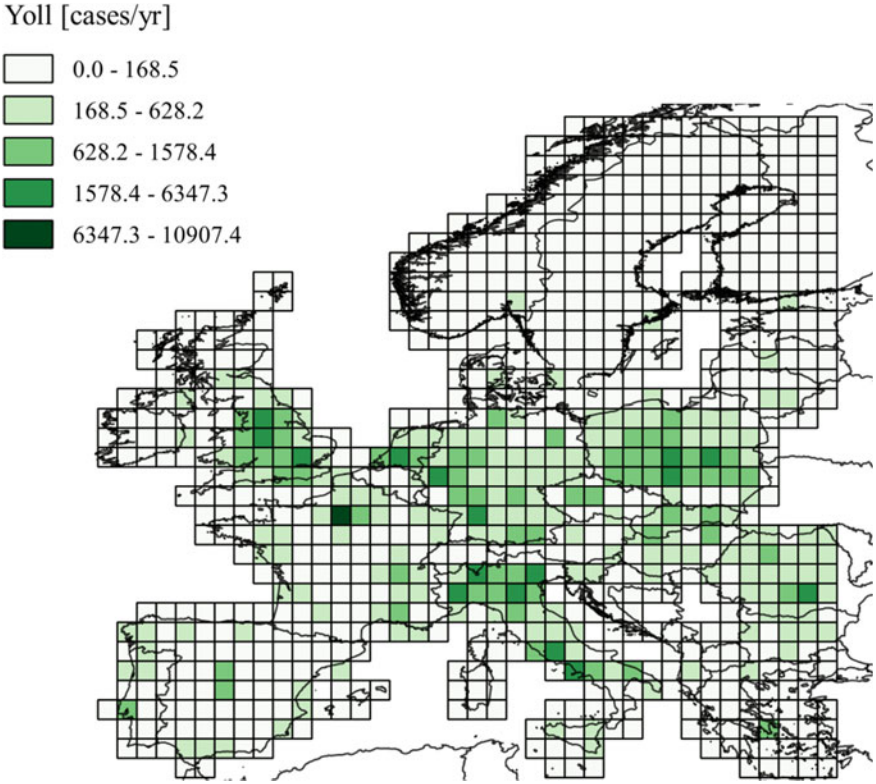

Fig. 15.6 The difference between the value of YOLL in 2015 and 2050 (High-RES centralized scenario) at the grid-cell level. Green color shows the benefits resulting from better air quality. (*Source* Own illustration)

Table 15.4 Annual external attributed to $PM_{2.5}$ exposure in 2015 and 2050 (Mod-RES)

Type	Health impacts		External costs		
	2015 [10^3 cases]	2050 [10^3 cases]	Monetary value [EUR_{2013} $case^{-1}$]	2015 [10^9 EUR]	2050 [10^9 EUR]
YOLL	2401	2166	57,510	138.0	124.6
RAD	235,895	212,853	98	23.1	20.9
CB	219	198	38,578	8.5	7.6
Total				169.6	153.1

15.3.1 Summary and Conclusions

In this study the air quality and health impacts of direct emissions of pollutants associated with the energy scenarios elaborated within the REFLEX project are assessed. According to the REFLEX scenarios, the emission in 2050 as compared to 2015 will be ca. 30 times lower in the residential and tertiary sector, 3 times lower in road transport and 12 times lower in the power and district heating generation. This is caused both by limiting the combustion of solid fuels and by improving combustion methods. The difference in $PM_{2.5}$ emissions between REFLEX scenarios in 2050 is insignificant. This is mainly due to the different structural use of solid biomass for heating. In decentralized scenario, with higher emissions, more biomass is directly used by households. In centralized scenario, biomass is used in combined heat and power plants with better emission control.

Results show that as compared to the situation in 2015 there are improvements in air quality and also the negative health effects are reduced in 2050 in all REFLEX scenarios. The largest of 5 $\mu g/m^3$ improvement in air quality regarding $PM_{2.5}$ concentration is observed in Poland. Increasing the spatial resolution of the air quality modeling domain would allow to observe even greater differences of concentration in some areas, as the reduction of emissions per unit area would be even greater. Choice of the settings is dictated by the high requirements of computational resources and the computation time, which significantly increases with the increase in resolution. Generally, a greater improvement in air quality is observed in Eastern and Central Europe due to the significant reduction of emissions from the residential sector. The cumulative number of years of life lost in the Mod-RES scenario in 2050 amount to almost 2.2 million. The results of the health impact assessment are almost the same for the High-RES scenarios due to similar PM emissions and ambient pollutants concentration levels in these scenarios. The estimated reduction of external costs according to Mod-RES scenario in 2050 as compared to 2015 situation reaches almost 20 billion EUR per year.

In this study the changes of PM emissions only from selected sectors (i.e. road transport, power and district heating generation, households and tertiary sector) are taken into account. Anthropogenic emissions from other sectors such as e.g., industry or agriculture are maintained at a constant 2015 level. The same applies to the natural emissions and to the boundary conditions that take into account the inflow of PMs emitted outside of the analyzed domain. Therefore, the significant reduction in PM emissions observed in the analyzed sectors in 2050 do not yield a proportional decrease of ambient PM concentration. Hence, also health benefits, which take place in all the countries, are moderate. The results show that the situation with regard to fine particulate air pollution and associated health impact will continue to improve in the future due to two main factors. Firstly, exhaust systems are getting improved and the effectiveness of flue gas cleaning is increasing. Secondly, the role of fossil fuels (i.e. their combustion) will decrease.

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Part VI
Concluding Remarks

Chapter 16
Summary, Conclusion and Recommendations

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Abstract This chapter summarizes insights and measures to decarbonize the European energy system until the year 2050, as analyzed in the previous 15 chapters, and emphasizes the considerable efforts required to coordinate and govern the targeted energy transition. With increasing aspiration regarding the targeted climate policy the more marked are the required efforts. The reference scenario Mod-RES seems to be well achievable from today's perspective, while much more additional efforts have to be taken to achieve the more ambitious High-RES scenarios. However, even the High-RES scenarios are less aspiring compared to the aims defined in the European Green Deal. Finally, this chapter highlights conclusions and policy recommendations for a cross-sectoral decarbonization as well as for its resulting environmental, social and health impacts.

16.1 Summary

The core objective of the book is to analyze and evaluate the development toward a low-carbon energy system in Europe up to the year 2050 with focus on flexibility options—i.e., storages, grids, electric vehicles, demand side management (DSM) and power–to–x technologies as well as curtailment to support a better system integration of renewable energy sources (RES). To achieve the target of significant greenhouse

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gas emission reductions or even being climate neutral until 2050, considerable efforts are a condicio sine qua non. Above all, robust CO_2 price incentives and a strong reduction of the CO_2 emission cap are essential. In the scenarios, CO_2 prices range between moderate 34 EUR/t_{CO2} (in Mod-RES) and 70 EUR/t_{CO2} (in High-RES) in 2030 and between 90 EUR/t_{CO2} and 150 EUR/t_{CO2} in 2050. While the Mod-RES scenario seems to be well achievable from today's perspective, but fails with regard to the targeted emission reduction in 2050, both High-RES scenarios are much more ambitious and need additional, more effective policy measures and incentives than today (cf. Chapter 2). Besides a strong carbon price incentive, results show that the following *four main pillars* are the basis of a successful climate-neutral transformation of the energy system in the next decades:

- (Significant) increase of renewable energy sources (RES) to generate almost CO_2-neutral electricity as called for in the European Green Deal—a factor of 4 to 6 of today's RES installations in 2050. Challenges occur to integrate these large amounts of additional renewable energy sources. Results have shown that in the High–RES decentralized scenario demand side flexibility (e.g. PV–battery systems, battery electric vehicles, heat pumps, etc.) is more important than in the High–RES centralized scenario, where infrastructure for sector coupling as well as power grids play a crucial role. In both High–RES scenarios back-up capacities are still highly relevant.
- Increase of energy efficiency to reduce energy consumption while maintaining the energy service levels and thus contributing to a lower energy demand at all scales and sectors (industry, mobility, buildings etc.).
- Increase of electrification by means of sector coupling (power-to-x technologies), to make use of higher shares of renewable energy sources for providing heat and mobility services.
- Use of CO_2-neutral hydrogen for energy services in particular in industry and for energy needs with high energy density.

Hereafter preconditions and instruments needed to implement strategies based on these four pillars are explicated and some related implications are highlighted.

16.1.1 Electricity Sector

16.1.1.1 Economic Incentives

A strong carbon price increase until 2050 drives the electricity supply side to a fuel switch toward gas-fired power plants[1]. Up to renewable shares of 80% across Europe, investments in electricity storage technologies are barely cost-effective. Ensuring a proper CO_2 price signal as well as support for multi-purpose use of utility-scale electricity storage is crucial in order to steer the future technology mix.

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[1] It is assumed that the transformation will mainly be driven by costs (relative cost-effectiveness).

Despite the strong growth of renewable capacities substituting large amounts of fossil fuels, carbon capture and storage is necessary for remaining fossil fuel technologies (providing back-up capacities) to achieve the emission reduction targets in the High-RES scenario.

16.1.1.2 Regulations

The still uncoordinated national energy policies, manifested in the diverse national capacity remuneration mechanisms (CRMs), could lead to substantial cross-border effects in the future. Interconnectors should therefore be eligible to participate in capacity remuneration mechanisms of neighboring countries in order to avoid market distortions. Alternatively, a coordinated European capacity remuneration mechanism maybe considered.

On the electricity demand side, current conditions are not sufficient to establish functioning markets for demand side management. The participation of demand side management in the reserve markets should therefore be facilitated. Moreover, highlighting existing successful examples of demand side flexibility provision may alter the risk perception of companies and may raise additional demand side management potential.

16.1.2 Demand Side Sectors

16.1.2.1 Industry Sector

In the industry sector there are still untapped potentials of energy and material efficiency as well as process and energy carrier substitution. Depending on the industry sector and the different process various options are available to curb demand and GHG emissions. Examples are high-temperature heat pumps that better integrate different processes or electrical or physical approaches that replace thermal ones. To implement these options a broad set of measures is required to complement the main instrument, which is setting a price to carbon (through an effective cap in the ETS and through a CO_2 tax in the case of the non-energy intensive sectors). The main economic instrument needs to be complemented by specific measures such as audits, low-interest loans and ongoing education and training, fostered and complemented by entrepreneurial innovation. Next to tapping these existing potentials substantial research and development activities need to take place in the coming decade, in order to have ready new process technologies and innovations for the industry sector by 2030.

16.1.2.2 Transport Sector

A bundle of complementary measures is required to support the transition of the transport sector toward low-emission mobility. The introduction of fuel efficiency and CO_2 standards for new vehicles of all kinds represents a fundamental instrument to reduce greenhouse gas (GHG) emissions. Moreover, investments in the rail and public transport systems are needed to increase the attractiveness of these efficient travel modes. Policies supporting electric drive technologies by increasing their financial attractiveness over conventional fuel vehicles include vehicle registration taxes, road charges and fuel taxes. These measures are instrumental during the rollout of technologies (short-term), while electric drive technologies will likely be competitive in mid-term due to cost decrease based on high learning rates, especially for private car and light duty vehicles. Biofuels and synthetic fuels are less efficient options, yet reasonable for aviation and ships, where mature low-emission drive technologies will not be developed in the near future.

16.1.2.3 Buildings and Heating Sector

Current EU regulations regarding residential and tertiary buildings address only new buildings and a part of appliances. However, additional effort is required to increase the energy efficiency of the existing building stock, both in terms building technologies (e.g. lighting, ventilation, pumping) and in terms of thermal demand for heating and cooling. Indeed, for the deployment of renewable energy sources refurbishment is almost a prerequisite, due to technical reasons and due to limited availability of RES. With regard to district heating (DH), significant GHG emission reductions of 60–85% in 2050 are achievable. Particularly in countries with already well-developed district heating networks, biomass will play an important role in substituting fossil fuels. With the development of low-energy buildings, district heating and other innovative energy networks should be expanded in regions where sufficient spatial heat and cold density exists and/or if other options to tap RES are difficult or hardly feasible to implement with decentralized systems (e.g. to tap ambient heat from lakes, rivers, ground sources and to provide it to buildings in urban contexts).

16.1.3 Environmental Impacts

Two main environmental impacts could impede the transition process for a low-carbon electricity system identified in this book. Land use is significantly increasing with the expansion of renewable technologies and requires attention to be paid to infrastructure planning among EU member states with different regulations. Furthermore, the demand for metal will significantly increase. Results indicate that the transformation process to a low-carbon electricity system is highly dependent on the availability of metals to produce technologies for intermittent electricity generation.

In the case of battery based approaches for storage and mobility, metals strongly based on so-called rare earths are used.

16.2 Conclusions and Recommendations

16.2.1 Electricity Sector

16.2.1.1 Low-Carbon Supply Technologies and Flexibility Options

Besides the increase of renewable energy sources, a fuel switch toward gas-fired power plants can be observed. While CO_2 prices in Mod-RES are not sufficient to incentivize investments in carbon capture and storage (CCS) technologies, CCS becomes favorable in High-RES between 2040 and 2050 due to a CO_2 price up to 150 EUR/t_{CO2}. Since many conventional power plants in Europe are reaching the end of their lifetime in the upcoming decade, substantial amounts of new generation capacity will be required. In general, the modeling results indicate, that under the given scenario framework and the input from the model coupling within REFLEX, back-up capacities are necessary to provide system flexibility. Although the High-RES scenarios are characterized by relatively high shares of RES, CO_2 prices higher than 70 EUR/t_{CO2} are required to enforce decarbonization by avoiding investments in carbon-intensive generation technologies in the presence of an increasing electrification of the demand side sectors. High fuel and CO_2 prices can incentivize the competitiveness of low-carbon technologies like renewable energy technologies and CCS as well as flexibility options, such as storages and power-to-x. These results support existing analyses and policy recommendations, e.g., Capros et al. 2016 or Mantzos et al. 2019. Policy makers are therefore advised to continuously monitor the proper functioning of the EU Emissions Trading System (ETS) in order to ensure reasonable CO_2 price signals as early as possible. The insights gained in Chapter 10 highlight the need for a reformation of the EU Emission Trading Scheme. To enable high CO_2 prices which would provide long-term clarity and certainty in price developments, the CO_2 emission cap should be continuously adapted and synchronized with the RES expansion as well as with economic structural changes and more CO_2 emitting sectors should be included. Nevertheless, an even more ambitious RES expansion leads to significant reductions in fossil fuel-based electricity generation and at the same time increases the value of storage technologies. Furthermore, high shares of RES allow for a mix of various flexibility options in the electricity market in a cross-sectoral energy system.

With regard to utility-scale electricity storages, the assumed cost decreases of lithium-ion and redox-flow batteries (cf. Chapter 4) are not sufficient to achieve a high market penetration of these technologies when renewable electricity generation contributes to the electricity demand at shares of around 60%[2]. Even up to average RES shares of 80% across Europe, investments in storage technologies (including pump storage power plants, where specific regional conditions are essential for profitability) are barely cost-effective and therefore do not play a major role. These findings underline the importance of rapid cost decreases for electricity storage technologies as they are required for even higher RES shares, for instance, in a Green Deal scenario. In order to foster the market penetration of electricity storages, policy makers should support their multi-purpose use (e.g., the provision of ancillary services additional to the use on the day-ahead market). An increased diffusion of utility-scale storages could then in turn reduce curtailment of electricity from RES surplus feed-ins as well as decrease the need for conventional back-up capacities and thus enable savings of total system costs. Moreover, the necessity of promoting DSM could be reduced (cf. Section 16.2.1.3), as storage systems and DSM are competing flexibility options. Since DSM smooths the residual load, electricity market-based storages decrease in value – vice versa. Nevertheless, an extensive application of DSM, as in the High-RES decentralized scenario, can lead to significant reductions of positive residual load peaks, thus limiting the need for additional (conventional) back-up capacities, but also increases full load hours of flexible technologies. However, sector coupling increases electricity demand and thus more ambitious RES expansion is necessary, especially if additional greenhouse gas emissions resulting from conventional power plant capacities shall be avoided. Hence, both storage and DSM options will be needed.

A more decentralized future energy system substantially differs from a more centralized one, as the comparison within the two REFLEX High-RES scenarios reveals, particularly regarding the interactions of different sectors: In the High-RES decentralized scenario the role of the residential sector as decentral flexibility source (especially heat pumps, electric vehicles, PV battery storage systems) increases strongly and thus weakens the role of further flexibility options (like pump storages) in the electricity market. In the High-RES centralized scenario, large-scale solutions especially for sector coupling (amongst others centralized electrolyzers for H_2 production (cf. Chapter 7 and 8) and renewable integration, increase of centralized heat production (cf. Chapter 12)) become relevant. However, both (more ambitious) scenarios span a broad development of renewable expansion and should not be understood as either the one or the other, but exploiting a combination of both scenarios and making use of the renewable potentials will be essential. In both scenarios, a higher amount of renewable energies is important to achieve emission reduction targets and is a no regret strategy, as especially shown within the sensitivity analysis toward higher shares of renewable technologies (cf. Chapter 10).

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[2] Although renewable energies are considerably expanded until 2050, the share only rises to approx. 60% in the High-RES scenarios, since in the same time electricity demand increases from approx. 3,000 TWh in 2014 to 5,000 TWh in 2050. Sensitivities with higher RES shares are calculated in Chapter 10.

16.2.1.2 Electricity Market Designs

Concerning the impact of electricity market designs (cf. Chapter 11) on generation adequacy, results show that the introduction of a capacity remuneration mechanism (CRM) is an effective measure substantially shifting investment incentives toward the countries implementing the mechanism. This effect is most pronounced in settings with a moderate growth of the electricity demand (as in Mod-RES), where open cycle gas turbines (OCGT) are often the most profitable investment option. Consequently, investments in peak load power plants are carried out in countries with an active capacity remuneration mechanism, while neighboring countries without an own capacity remuneration mechanism face significantly lower capacity levels and are therefore confronted with increasing wholesale electricity prices in the long run. If the electricity demand grows rapidly (as in High-RES), investments in combined cycle gas turbines (CCGT) are often economically preferable over peak load capacities. Moreover, and in contrast to open cycle gas turbines, the profitability of combined cycle gas turbines in countries without a capacity remuneration mechanism is less affected by additional investments in neighboring countries with capacity remuneration mechanism due to higher full load hours. Consequently, the wholesale electricity prices may also decline in countries without an active capacity remuneration mechanism in the long-term.

Capacity remuneration mechanism could force investments in electricity storages, if an average share of electricity from renewable sources around 80% across Europe is achieved. This is driven by the additional revenues from the capacity remuneration mechanism. However, due to the technology-neutral approach of the capacity remuneration mechanism as desired by the European Commission, the cost-effectiveness of non-storage technologies such as open cycle gas turbines increases when a capacity remuneration mechanism is implemented. However, building more peak load capacity in countries with an active capacity remuneration mechanism, drastically reduces investment incentives in neighboring countries without an own capacity remuneration mechanism.

Thus, whether positive or negative cross-border impacts of capacity remuneration mechanisms prevail, will depend on the specific setting. In general, capacity remuneration mechanisms seem to increase generation adequacy not only in countries implementing the mechanism, but also in the neighboring countries. This finding indicates that free riding occurs. In order to avoid these market distortions, a coordinated European capacity remuneration mechanism as electricity market design is recommended.

16.2.1.3 Demand Side Management

Although in some European countries favorable regulatory conditions for demand side management exist, their conditions are not sufficient to establish functioning demand side management markets and attract companies' interest. As of today, particularly small demand units are hardly participating in demand side management although on aggregate level their potential would be high. Lacks of (reliable) information and of financial benefits as well as perceived risks have empirically been identified to be relevant barriers against the adoption of more demand side management options especially in the tertiary sector (cf. Chapter 8 and Reiter et al. 2020).

Specific policy measures are required to reduce those barriers across all countries. For instance, implementation rates and the respective compliances with the EU regulation could be increased, and the varying settings in different countries reduced, allowing market players to be active in multiple countries and therefore, attracting business opportunities. Special focus has to be put on the bid size and aggregation of demand side management potentials to participate in the reserve markets.

Additionally, by showcasing existing examples of how flexibility providers can benefit from participating in demand side management markets, risk perception of companies may be altered, offering additional demand side management potentials. As the risk perception differs to a high degree between countries, specific approaches (e.g., from aggregators) are needed to highlight potential economic advantages. Besides market-based transaction schemes, information regarding technical implementation as well as the functionality of demand side management have to be provided to small- and mid-sized companies as they lack internal relevant know-how. Specific information can be best provided by independent stakeholders such as governmental energy agencies or independent energy advisors.

Larger companies with more standardized procedures regarding energy efficiency and energy demand might adopt demand side management models faster and therefore, integrating demand side management into energy management systems could support the further rollout of flexibility options on the demand side. Energy advisors and auditors can help to spread the word of advantages and disadvantages of demand side management systems.

Once again it should be emphasized, that the presence of storage systems could devalue DSM strategies and thus the propensity to invest in such options (cf. Chapter 9, 10).

16.2.2 Industry Sector

In the long-term, key measures enabling the decarbonization of the industry sector are radical changes to industrial production systems toward CO_2-neutral production processes and products (e.g., hydrogen processes and large-scale power-to-heat for steam generation and managing multi-temperature processes with industrial high-temperature heat pumps), mainly envisaged for implementation in the time horizon after 2030. Before 2030, energy efficiency improvements combined with fuel switching to biomass and progress adaption and innovation toward a circular economy are the main mitigation options. In order to have new CO_2-neutral process technologies and innovations ready by 2030, substantial research, development and innovation activities need to take place in the coming decade supported by the respective known policy measures (e.g. financing of research and development, public procurement, labelling, CO_2 price). Pilot and demonstration plants need to be built as well as new certification processes for new materials introduced. To further promote material efficiency and therefore directly reduce energy demand along the value chain, a broad policy mix is required. Implementing policies to overcome barriers to energy efficiency (energy management schemes, audits, low-interest loans, and energy service markets) is a prerequisite for other (price-based) policies to work effectively (e.g., CO_2 floor price to provide clarity for investment decisions, CO_2 tax for companies outside the EU ETS).

16.2.3 Transport Sector

In contrast to all other sectors, the transport sector increased its greenhouse gas emissions since 1990 (European Commission 2011). According to the European Strategy for Low-Emission Mobility the emissions in the transport sector need to be reduced at least by 60% in 2050 compared to the level of 1990. Hence, the emissions should be clearly on the path toward zero by mid-century and air pollutants harming public health need to be drastically reduced without delay (European Commission 2016). Considering the continuous growth of passenger and freight transport demand, strong and timely responses are required at policy level. The analysis of the transport sector in the present book (cf. Chapter 5, 6 and 7) specifically considers global learning for batteries and flexibility potential provided for the electricity sector. Results indicate that a bundle of complementary measures is required to support and accelerate the transition. In the investigated High-RES scenario, the main drivers of CO_2 emission reduction are the diffusion of low- and zero-emission road vehicles (achieving 26% reduction in 2050 relative to 1990), efficiency improvements (adding up to 44%), and alternative fuels, in particular for aviation and navigation (reaching 58%). Policies aiming at modal shift to active modes, public transport and new mobility services (e.g., car sharing, mobility-as-a-service systems, autonomous cars) can contribute in particular on the local level. Although for the overall transport system the impact in the analyzed scenarios is lower compared to other strategies, these policies still contribute to CO_2 emission reduction for about 10%.

The main findings and policy recommendations are categorized by the three main European strategies for the decarbonization of the transport sector: (i) energy efficiency, (ii) electrification of road transport and (iii) alternative fuels.

16.2.3.1 Energy Efficiency

Energy efficiency is of utmost importance, but to reach the GHG targets in case of individual personal transport, the switch to e-vehicles in combination with higher

RES expansion is highly required. The introduction of fuel efficiency and CO_2 standards for new vehicles represents a fundamental instrument to reduce overall GHG transport emissions. These standards should not only be tightened for cars and vans but also extended to heavy duty vehicles, buses and airplanes. Such standards force the automotive industry to become innovative and to change their product portfolio to vehicles with alternative zero- and low-emission powertrains. Setting interim and long-term targets beyond 2030 ensures that investments are made soon and maintained based on long-term direction. The targets have the advantage to promote innovation while staying technology-independent which is relevant for transport modes for which several competing technologies are under development.

Infrastructure for high-speed train connections for well-used routes is an option to replace domestic as well as inner-European flights. For freight, transport on railways and inland waterways are more efficient transport solutions. To achieve shifts toward these more efficient transport solutions, investments in the rail and public transport systems within member states as well as on transnational level across member states are needed, but can hardly compensate the further growth in freight transport. In the High-RES scenarios, a part of road transport share is shifted to rail and inland waterways, in particular due to respective investments in railway and waterway infrastructure, in multimodal freight terminals and increased taxation of fossil fuel-based road transport. Furthermore, the development of integrated logistics can make a more efficient use of freight vehicles, enabled also by the diffusion of digital technologies. Measures related to urban freight logistic include a huge variety of different transport operations and logistics activities ranging from road network and parking strategies, terminals and modal interchange facilities, pricing strategies, ICT-based vehicle control systems, logistics information systems, etc. Within REFLEX, these types of policies have been simulated in the High-RES scenarios, contributing to the reduction of CO_2 emissions at urban level. However, road share increased again toward 2050 with the diffusion of low-emission fuel cell and battery electric trucks, thus showing a rebound effect.

Sustainable transport modes should be made more attractive and convenient, for example by urban planning measures and infrastructure provision in favor of active modes, by increasing spatial coverage and frequency, and by developing and promoting an ICT-based, integrated and transparent multimodal mobility system. It is fundamental to sustain modal shift especially for short-distance passenger transport where the vast majority of trips are concentrated. Indeed, urban areas show the most pressing congestion challenges but have also the highest potential for behavioral change and technology transition. Modal shift is mainly achieved for the High-RES decentralized scenario on the local level for passengers. The diffusion of shared mobility schemes in European cities, enhanced by the wide spread of information and communication devices, is becoming an alternative to individual transport means thus partly alleviating the problems related to congestion, air pollution and GHG emissions by reducing the number of vehicles in circulation. Within the REFLEX scenarios, car sharing and car-pooling policies have been tested and are an option for local mobility (especially in the High-RES decentralized scenario).

16.2.3.2 Electrification of Road Transport

Subsidies for low-emission vehicles are required in the first years of technology market entrance, when vehicle prices are still relatively high. Battery electric and plug-in hybrid electric vehicles are expected to contribute to a widespread electrification of passenger transport, as they will soon become competitive with conventional oil-based cars thanks to learning effects and economies of scale in global battery production and as public charging infrastructure is deployed. Thus, subsidies for vehicles as purchase incentives or bonus malus (or so-called fee bate) systems seem only reasonable within the next few years. Furthermore, monetary advantages for homeowners with rooftop photovoltaic systems, generating electricity for self-consumption, can contribute to the diffusion of battery electric vehicles. This factor would become more relevant, if the electricity system develops in a more decentralized way (as e.g. in the High-RES decentralized scenario).

Within the REFLEX High-RES scenario assumptions fuel cell electric vehicles would lead the technology transition for long-haul trucks. Although hydrogen production is less energy efficient compared to direct electrification, fuel cell electric trucks are assumed to become a real decarbonization option. Hydrogen production has the potential to provide flexibility to the electricity system that has to cope with fluctuating electricity feed-in by renewable energy sources. In times of electricity surpluses hydrogen could be produced, stored and reconverted to electricity when needed. Research and development as well as subsidies for fuel cell technologies seem still required to achieve competitive prices.

In general, policies that support the transition to new drive technologies by increasing their financial attractiveness compared to conventional fuel vehicles are vehicle registration taxes, road charges and fuel taxes which all depend on the respective CO_2 emissions.

16.2.3.3 Alternative Fuels

Biofuels and synthetic fuels based on electrolysis and additional treatments, i.e., power-to-gas (PtG) and power-to-liquid (PtL), are less efficient options for low-carbon transport, as production requires biomass as resource and renewable electricity as energy source with low degrees of efficiency in internal combustion engines. However, they should be used for modes for which mature low-emission drive technologies will not be developed in the near future. This is mainly the case for aviation and for ships. Alternative fuels also play at least an intermediate role for road transport, if battery range anxieties result in a higher diffusion of plug-in-hybrid cars for longer distances. Moreover, new technologies for trucks might not become adequate for certain special purpose vehicles by mid-century. A clear strategy for using sustainable biofuels and synthetic fuels in selected applications (aviation and ships) is then needed. The production of advanced biofuels should be supported. When sustainable production can be ensured for certain quantities, blending quotas of biofuels and power-to-x (PtX) fuels could be established.

Greenhouse gas emissions reduction in the REFLEX scenarios is obtained assuming that transport performance grows with increased gross domestic product, income and population until 2050. Future research and policies might focus also on measures investigating how demand can be reduced while still meeting citizens' needs, for example by spatial planning measures and opportunities appearing with increasing digitalization. The three mobility packages presented by the European Commission (2018) set the right direction. Their principles should be enhanced and adopted as binding directives either on European or on national level to ensure implementation.

16.2.4 Heating Sector

In the heating sector two crucial aspects and policy recommendations can be derived based on the REFLEX results (cf. Chapter 12): energy efficiency in buildings and district heating networks.

16.2.4.1 Energy Efficiency

In the buildings sector (residential and tertiary), the potentials for improved energy efficiency are even higher than in industry. Currently, low building renovation rates limit the fast uptake of energy efficiency potentials and the switch to renewable heat sources. Currently, efficiency progress in the buildings sector is mainly driven by EU regulations like the Energy Performance of Buildings Directive (EPBD) and the Ecodesign Directive. However, these directives mainly address new buildings and appliances. Therefore, tapping additional efficiency potentials in the existing building stock requires additional efforts (e.g. subsidies, incentives, binding targets as well as removal of barriers and changes of personal behavior). To tap these available potentials, combined efforts in targeting refurbishment rates, refurbishment depths and technology change are needed. Refurbishment is a prerequisite for the deployment of RES, both for technical reasons (low heat distribution temperature enable high heat pump efficiency) and due to limited availability of RES potentials. For an effective diffusion of RES for space heat supply, the regulatory frame needs to be adapted to make RES cost competitive compared to fossil-based solutions. This holds irrespective of the underlying setting of the heat sector, i.e., whether more decentralized or more centralized.

Likewise energy efficiency in the industry sector needs to be increased. Process management and adaption to decrease useful heat temperature levels of processes and energy management between processes of different temperature levels (including cooling and freezing) offer substantial potentials to reduce final energy demand by using high-temperature heat pumps. This enables the use of renewable ambient heat sources in the respective sectors (e.g. chemicals, pharmaceuticals, food and beverage), either in centralized or decentralized ways. This reduces the need and high-exergy fuels (e.g. biomass, PtG, H_2) which should be used for remaining of high-temperature energy needs, e.g., in the cement and metal industries.

16.2.4.2 District Heating Networks

Besides heat pumps at household level (cf. Chapter 7, 9 and 10), also district heating can be a facilitator to decarbonize the heat sector (cf. Chapter 12). To allow for a more centralized provision of renewable heat and to tap the full potential of thermal energy networks (e.g. district heating networks, cold networks, ambient heat, multi-purpose etc.), economic and financial instruments (e.g. incentives, preferential loans, risk mitigation mechanisms) as well as connection regulations and strategies are needed. Respective system integration needs to be supported by regulations toward connection management and excess heat disposal. Policies can additionally support the uptake by e.g., hedging high risks in individual projects, regulating excess heat release in national emission control acts, strengthening local heat planning and providing investment grants. The management and support of specific geothermal potential zones as well as further cost reductions are needed to achieve major growth of large-scale heat pump installations for district heating supply.

The development of the district heating systems in the future depends on the district heating demand, which varies in the REFLEX scenarios. The demand increases in the High-RES centralized scenario whereas in the Mod-RES and High-RES decentralized scenarios it is expected to be lower than today. Further factors influencing the modeling results are CO_2 emission allowances prices of the EU ETS market, techno-economic parameters of processes employed in district heating systems as well as potential and costs of fuels and energy resources. Results show that significant GHG emission reductions are possible in the district heating generation sector from approximately 60% to 85% in 2050 depending on the REFLEX scenario. As a response to increasing CO_2 prices, bioenergy (mainly biomass) capacities are growing significantly. Therefore, biomass can play an important role in substituting fossil fuels in district heating generation in particular in the EU member states where the district heating networks are already well developed. Natural gas is still used due to high flexibility also in terms of the power-to-heat (PtH) production ratios.

With decreasing district heating demand, as in case of the Mod-RES and High-RES decentralized scenario, combined heat and power plants are exposed to lower district heating sales but also to lower electricity sales. With decreasing district heating demand and with a simultaneous increase in electricity demand – as in the case of the High-RES decentralized scenario – it is impossible to maintain the current relative share of electricity produced in cogeneration while meeting the cogeneration efficiency goals. In fact, in this scenario the share decreases from the current 12% to 7% in 2050. In case of the High-RES centralized scenario, the increased district heating demand has to be associated with developments of new district heating systems. Additionally, it is important to design district heating systems for low-temperature renewables sources such as ambient energy from lakes, rivers, air and geothermal ones. The transition toward higher use of bioenergy (mainly biomass) requires sustainable adequate concepts (e.g. biomass only to supply peak loads) and organizational (logistic) solutions that will minimize energy and CO_2 emissions embedded in processing and transportation.

Short-term heat storages help to smooth the generation profiles and seasonal storages increase the heat produced in summer times and consumed in winter times. The use of PtH technologies including large heat pumps depends on electricity prices but certainly helps to manage the RES electricity surplus that otherwise would be curtailed. Additionally, district heating networks allow – among others – for integrating excess heat from industrial activities. If industries are nearby, higher temperature levels can contribute to the efficient use of heat in industrial parks.

In general, district heating costs are increasing in future years. This is mainly due to the investments in new capacities, rising CO_2 prices (if fossil fuels are used) and increasing fuel costs. Therefore, it is necessary to maintain the existing or new implemented policy measures that will guarantee necessary profits for generators and keep the district heating end-user prices at competitive levels. With the development of low-energy buildings, district heating networks should be expanded in regions where sufficient spatial heat density exists in order to maintain the current district heating demand.

16.2.5 Environmental, Social Life Cycle and Health Impact Assessment

Although the focus of the energy transition is mostly on climate change, the impacts of an energy transition of health, environment and society could promote, but also impede the transition process.

With both by limiting the combustion of solid fuels and by improving combustion methods, positive impacts on the health are expected. Due to the energy transition the ambient concentration of air pollutants in 2050 will be lower compared to 2015 by around 30 times in the residential and tertiary sector, 3 times in road transport and 12 times lower in the power and district heating generation sector, respectively (cf. Chapter 15). This will increase noteworthy the air quality and by this air-borne health effect will diminish in all REFLEX scenarios. The largest of improvement in air quality regarding $PM_{2.5}$ concertation is observed in Poland with around 5 $\mu g/m^3$.

Beyond GHG emissions most analyzed environmental impacts of the transformation of the energy system follow the share of renewable energy sources at the energy provision, i.e., the impacts decline as the share of renewables increases.

Two environmental impacts could impede the transition process for a low-carbon electricity system. First, land use is significantly increasing due to renewable technologies and requires attention to be paid to infrastructure planning among EU member states with different regulations. Land use for ground mounted PV in the base year (2014) amounts to only 3% of that required in 2050 for the High-RES decentralized scenario – 950 km^2 compared to 28,864 km^2 (cf. Chapter 13). Countries with best weather conditions for ground mounted PV (France, Italy, Spain and other Mediterranean countries) have their restrictions that consider aesthetic requirements as well as the potential for resident opposition (NIMBY – not in my back yard). Second, metal depletion results demonstrate that the transformation process to a low-carbon electricity system is highly dependent on the availability of metals (finite resources) to produce technologies for intermittent electricity generation.

Looking at different social impacts, like child labor, fair salary, forced labor and workers' rights (except for health and safety), the energy transition could push to in-depth discussion about a (international) fair distribution of the gains. Following the findings in Chapter 14, in respect to the above listed categories in all analyzed scenarios the situation will be worsen. Compared to 2015. The main reason is the growing share of gas-based generation in future. Gas technologies have higher than average impact considered per unit electricity generation due to its "fuel supply chain", of which is originated mainly outside the EU, that is responsible for over 90% of total impacts caused by gas-based generation. Solar power and wind power make more modest contributions in all impact categories. Nevertheless, due to the increase in PV share in the electricity mix, solar's contribution to social impacts grows up to 2050. The contribution analysis shows that even in 2050 between 48% (for the subcategory fair salary) and 91% (for child labor) of the total contribution due to the ground mounted PV arises due to the processes "raw material extraction" and "material and component manufacture", which is also originated predominated outside the EU. Similar trends are observed for rooftop PV.

16.3 Further Aspects and Outlook

In general, the combined insights and measures to decarbonize the European energy system until the year 2050, as analyzed in this book, emphasize the considerable efforts required to coordinate and govern the targeted transition. This is especially true, as the European Green Deal – in line with the Paris Agreement – is even more ambitious with regard to emission reduction than the considered High-RES scenarios (cf. Chapter 1). The Mod-RES scenario seems to be well achievable from perspective of today's boundary conditions and some moderate adjustments, while much more additional efforts have to be taken to achieve the more ambitious High-RES scenarios. Both (ambitious) High-RES scenarios increase energy efficiency and span a broad development of renewable expansion and should not be understood as either the one or the other, but exploiting a combination of both scenarios and making use of the renewable potentials will be essential. In consequence, relevant measures have to be based on wide and stable acceptance across the member states. The support and promotion of the measures discussed influence the everyday life and coexistence of almost all EU citizens and requires the consent of stakeholders involved across all areas of society. The EU and the member states have to play a crucial role to pave the way to achieve the transformation targets.

The European Green Deal goes beyond the emission reduction in the High-RES scenarios by targeting climate neutrality until 2050 and thus the required transformation processes are even more challenging than the scenarios analyzed in this book. Although climate neutrality has not been assessed, results indicate the importance of hydrogen.

In addition to the four main pillars mentioned at the beginning of this chapter, following *preconditions for a successful transformation*, without claiming to be complete, need to be guaranteed:

- *Promotion and strengthening of European integration and harmonization of common goals across the member states, yet adopting the subsidiary principle taking individual preconditions, potentials and motivations into account, to*
  - Leverages costs and burdens,
  - To use available resources efficiently,
  - And to comprise that fact that the energy market is European, and thus to strengthen market-based solutions as well as a fair competition among flexibility options to integrate renewable energy sources.
- *Do not lose time to*
  - Improve implementation.
  - Establish long-term agreements and targets to ensure investment and planning security.
  - Further increase efforts regarding research and development (including research toward a hydrogen economy in a European energy system).
  - Strengthen a transparent communication of targets, benefits and challenges to the public based on scientific and public discussions.

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