CICC Research, CICC Global Institute

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Preface—Unquenchable Flames: The Rise of China's Innovation Economy

The COVID-19 pandemic has again brought the role of technology into the spotlight. Had the pandemic occurred just 10 years earlier, the economic costs of social distancing measures would have been much higher. Technology significantly aided efforts to contain the spread of COVID-19, and this, in turn, spurred further technological innovations. For example, vaccine development that would likely have taken 10 years in the past was completed in a mere 10 months. Digital commerce made it possible to maintain essential economic activities at reasonable levels despite extensive social distancing. The fight against COVID-19 foregrounds the vital importance of technological innovations.

At the same time, the pandemic has encouraged greater concerns with human life in technological advances. For instance, a debate in the early stages of the pandemic was about whether to prioritize individual lives over economic growth, and it was clear that the two goals were not really contradictory. With the growing consensus that humans should live in harmony with nature, the green transformation has become a new driving force behind technological innovations around the world. The accelerating digital transformation made 2020 a stellar year for large digital platforms. However, it was quickly followed by a new phase of enhanced digital governance and regulation featuring a wave of antitrust actions, crackdowns on unfair competition, and a stronger emphasis on privacy protection. The disruptions from COVID-19 also revealed that the resilience and security of industry chains, besides efficiency, were essential for economic stability and international competition.

As China embarks on a new stage of development, a new growth paradigm with novel growth thinking has come to the fore to steer the country towards high-quality development. Technological innovations and common prosperity are vital issues in this new era. To effectively implement the 14th Five-Year Plan and achieve the long-term objectives through 2035, China can seek to properly balance the trade-offs between efficiency and equality. In essence, technological innovations are an economic activity that requires a favorable environment and effective incentive mechanisms. While raising productivity, innovation would also inevitably affect all sides of production. This brings us to several questions yet to be answered. How can

China foster technological innovations? How can the security of industry chains be guaranteed and improved? What are the key sectors for future development?

This book is a collaboration between the CICC's Research Department (with contributions from the macro, strategy, and sector teams) and CICC Global Institute (CGI) to offer a comprehensive analysis of the development of technological innovations in China. In the book, we strive to investigate the existing challenges and discuss the role of public policy. Chapters 1 and 2 provide the macro background of this book. Chapter 1 analyzes the current conditions and challenges for technological innovations in China, with a focus on the supply side of innovations (e.g., talent and R&D) and various risks and challenges brought by the ongoing global competition. Chapter 2 emphasizes the role of scale effects in fostering technological innovations, with a focus on the demand side of innovations, both domestic and international. Chapters 3–6 focus on specific sectors, namely the most innovative sectors—digital, biological, and green sectors, as well as the manufacturing and logistics sectors where technological innovations play a fundamental role. These chapters analyze the industry chain security and innovation potentials of these strategically important sectors. Chapter 7 emphasizes the importance of innovation policy. It discusses ways to support innovation by improving the national innovation system, in which regional innovation centers and the financial system are important factors.

Economics of Innovation

Technology is crucial to economic activities, by determining how goods are produced with raw materials, labor, and machinery, among others. Technological progress enables us to produce more goods with the same amount of inputs, and is therefore the ultimate engine of economic growth. Although this is a consensus today, economists' views on this issue have evolved over time. Early classical economists believed that economic growth was determined by the savings ratio of a given population, which implied that the key to economic growth was to increase savings—i.e., investment. In other words, classical economists thought that economic growth would double if the savings ratio doubled. In a nutshell, classical theories focused on the accumulation and reproduction of production factors, but overlooked the importance of technological advancement.

Why was technological progress left out? One possible explanation is that classical economic theories were based on socioeconomic conditions prior to the Industrial Revolution, when technological breakthroughs were limited. Most technological advances in that period were mere patches to existing production processes. However, rapid and sustained technological advancement since the start of the Industrial Revolution not only improved living standards substantially but also attracted increasing attention from economists. Karl Marx took the lead in examining the social impact of technological progress, and how advances in productive forces affected the relations of production and eventually the social structure. By combining innovation with entrepreneurship, Joseph Schumpeter went on to analyze the dynamic process of technological innovation as creative destruction in capitalist market economies.

Robert Solow's growth model is a typical example of mainstream modern economic theory. Solow's model shows technological progress as the sole engine of growth in the long run as marginal investment returns decline over time. The empirical evidence for Solow's model exhibits that most of the economic growth of the US in the first half of the twentieth century was driven by technological advances. Solow insightfully revealed the dynamic nature of the market economy rather than perceiving it as static and balanced. He pointed out that technological innovation would lead to new applications, and the expansion of these applications would in turn fuel more extensive technological advances, raising productivity, wages, income, and living standards.

It is then natural to ask what drives technological progress. Solow perceived technological advancement as an economic force that is exogenous to the economic system but did not explain its underlying drivers from an economic perspective. On the other hand, endogenous growth models, such as the Romer model, view technological advancement as an endogenous force and a result of innovation within the economic system. Economic benefits are essential drivers of R&D spending, human resource development, as well as productive capital investment to support applications of new technologies. Since the 1990s, both scholars and policymakers have paid increasing attention to the mechanisms and patterns of technological innovation.

In economic analysis, innovation can be classified into two categories: Radical innovation that leads to technological breakthroughs, and incremental innovation that gradually ameliorates existing technologies. In reality, radical and incremental innovations are often intertwined. From a macro perspective, a wave of innovation with major impacts on the economy (e.g., digital technologies) typically consists of three stages: The advent of revolutionary technologies, the diffusion of their applications, and eventually changes in lifestyles and economic patterns when new technology applications sufficiently penetrate. Both radical and incremental innovations take place in this process.

Unlike usual economic activities, technological innovation exhibits a number of unique characteristics. First, from a temporal perspective, technological innovation has clear cumulative effects and exhibits path dependence. A focus on long-term gains ("long-termism") is conducive to innovation, while excessive attention to short-term gains infers the opposite. This is why traditional cost-benefit analysis would in general thwart innovation, as the costs of innovation can be easily quantified while its future benefits are subject to significant uncertainties. For example, low-risk, short-term innovation would gain higher priority if decision-makers rely on cost-benefit analysis to rank projects. This naturally gives rise to the role of finance inherently related to innovation, as it is tasked with the essential process of intertemporally allocating resources amid uncertainties.

Second, from a spatial perspective, innovation has two seemingly opposite effects—the clustering and diffusive effects. The clustering of innovation results from the rise of regional innovation centers, while diffusion is attributable to the formation of global industry chains. The concentration of economic activities and production factors in major cities leads to economies of scale and scope. In particular, close interpersonal interactions in big cities help stimulate and disseminate new ideas and technologies. Meanwhile, technological advancements facilitate the professional division of labor across different parts of the world by mitigating distance-related problems. Therefore, technological progress not only contributes to but also benefits from, the formation of global industry chains. However, the divergent spatial layout and lengthening of industry chains have raised stability concerns, making the security of industry chains a new element of concern in technological innovation.

Technological progress is key to achieving China's envisioned high-quality development. The country's long-term objective through 2035 is to become a modernized socialist country and one of the world's most innovative countries with substantial improvements in economic and technological strengths. However, China is a latecomer in technological innovation and faces increasing disadvantages ("curse of the latecomer") as the country endeavors to catch up with frontrunners. In contrast, developed economies benefit from first-mover advantages in two key aspects: first, they have built more solid knowledge bases to support innovation (existing technological standards and network effects also benefit frontrunners); and second, countries with leading technologies, which are usually high-income economies, have a greater capacity to support R&D investment and can afford to be more patient with regard to future innovation outputs.

Given China's aging population, which resulted in issues such as the shrinking labor supply and declining savings ratio, we estimate that the country needs to increase its R&D intensity from 2.4 to 3.5% in order to raise its GDP per capita to the level of a moderately developed country by 2035. Based on current exchange rates, this implies China's total R&D expenditure would exceed that of the US and rank No. 1 in the world. We believe higher-than-average R&D expenditure is necessary for China to overcome its latecomer disadvantage and raise its total factor productivity.

R&D spending is just one factor of technological innovation. An effective innovation system should provide support and incentives for innovation, which should be effective and comprehensive. Innovation is a collective process involving various parties such as government agencies, private institutions (e.g., enterprises of all sizes), and social organizations (e.g., universities and social welfare organizations). The cultivation of innovation is a comprehensive and systematic project that requires proper handling of how the various participants interact, notably the coordination between the government and the market.

Establish Partnership Between Government and Market Participants

The two major schools of economic thought—i.e., Keynesian and neoclassical economics—hold completely different views on the relationship between the government and the market. Keynesian economists claim that investments are highly procyclical due to people's "animal spirits", which means governments should make countercyclical adjustments when the private sector is overly pessimistic. In contrast, neoclassical economists argue that government intervention stifles the vigor and vitality of the private sector, and as such, a free market is the only solution for effective resource allocation. In essence, neoclassical economists think that the government causes problems rather than solves them. In our opinion, neither Keynesian nor neoclassical economists provide a suitable theoretical framework for innovation. In an effective innovation system, the government should not only maintain macro stability by making countercyclical adjustments but, more importantly, also issue effective public policies at the meso and micro levels to provide motivation and incentives for innovation.

What underlies our views about the relationship between the government and the market? First of all, a key characteristic of knowledge is its non-rivalrous nature—the use of knowledge by one person does not prevent others from using it. It also suggests that technological innovation is embedded with positive externalities, since its cost is borne by individuals whereas its benefits are shared by the whole society. As a result, private sector investment in innovation is insufficient (compared to what's socially optimal). Moreover, innovation is a long-term, non-linear process with significant uncertainties. Private institutions have neither the patience to wait for success nor adequate risk tolerance to afford possible failures. The government, on the other hand, can help solve this problem.

The government may play two important roles in stimulating innovation. Firstly, it can directly participate in innovation by investing in R&D and education. A good example is the success of Silicon Valley. A common misconception is that the rise of Silicon Valley was driven solely by the private sector, notably startups and venture capital. However, the truth is that the government was the primary source of demand (by purchasing) and funding for early-stage R&D in many innovative companies. For example, the US federal government funded the development of nanotechnologies, and the Defense Advanced Research Projects Agency (DARPA) played a critical role in the development of fundamental internet technologies. In addition, the National Science Foundation (NSF) and the National Institutes of Health (NIH) jointly built the R&D framework for biotechnologies, and their investment in high-risk, long-term projects has made the US the primary source of innovative drugs for the whole world.

While both private and government-sponsored R&D projects could fail, the government has higher tolerance for individual project failures and is more patient in making long-term investments. The financial value of an R&D project is not an essential consideration of the government. In fact, the government may sponsor basic research without specific business value, or the development of revolutionary technologies with high risks and uncertainties. Moreover, public policies may also play a pivotal role in the development of incremental innovation. For example, the Chinese government supported electric vehicles in recent years and photovoltaic projects more than a decade ago. Despite initial controversy, government support has effectively boosted the development of both industries.

The government's second role is to design appropriate policies and mechanisms that can effectively motivate private institutions to pursue innovation. This role is even more controversial, and the most well-known case is probably the system of intellectual property protection, notably patents. The Austrian school of economists such as Friedrich Hayek firmly defended the free market and criticized the patent system as a monopoly deliberately devised and imposed by the government. They called for the abolition of intellectual property protection in order to restore the so-called "healthy" market competition. However, extensive micro and macro studies have indicated that the protection of intellectual property plays a critical role in technological innovation. At the end of the eighteenth century, the US established the modern patent system and introduced it to other parts of the world. Since then, the world has witnessed a plethora of inventions and technological innovations.

The patent system stimulates innovation in two ways. The first is through its ability to encourage investment, and the second, which is more subtle but important, is that patents can be traded so that the innovation process is separated from the production process, allowing inventors and manufacturers to focus on their respective specialties. Moreover, patents can be divided, bundled, or pledged as collateral to attract investment. In fact, the intellectual property system creates a marketplace that allows Adam Smith's "invisible hand" to play a more effective role in resource allocation. There are many other examples of government-devised market mechanisms, such as rules against monopoly, price manipulation, and unfair competition in markets for goods and services; trading rules and regulations in financial markets; as well as the launch of carbon trading markets.

As governments pay increasing attention to technological innovation, we should re-examine their role in this process. A common misconception in the past was that the government's role was quite limited in the US and other free-market economies. However, the reality is much more complex. In fact, the government's direct investment in R&D and education helped correct market failures. In addition, public policies were also indispensable to the formation of market mechanisms in these economies. It is clear that the government and the market are not adversaries. Instead, we think the public sector should partner with the private sector to construct market mechanisms conducive to innovation. A key issue in this partnership to be addressed is the relationship between monopoly and competition.

Antitrust Policies Should be Conducive to Innovation

Antitrust and anti-competition actions taken against platform companies by Chinese regulators have become hot topics. These are important issues as they not only protect consumer rights and fair competition in the digital era but also help establish a favorable market environment to support innovation.

In theory, monopolies could have both positive and negative impacts on innovation. Joseph Schumpeter pointed out that large firms with significant market power have higher motivation to innovate, greater ability to make long-term R&D

investments, and stronger resilience to failures. To better understand Schumpeter's logic, we analyze two possible scenarios: Firstly, monopolies (dominant firms in the markets) do not have to worry about free riders as there are no competitors to imitate the innovation achievement. Under these circumstances, monopoly firms would have strong motivation to reduce costs through innovation and gain excess returns; and secondly, innovation helps monopoly firms maintain their market power, as firms that do not innovate may be overtaken by potential competitors. Therefore, monopoly firms are motivated to innovate as long as the profits gained from the monopoly are higher than the costs of innovation.

In the US, we found that large firms that were not constrained by shareholders' short-term behavior (e.g., IBM, GE, AT&T, and DuPont) invested in basic research into frontier technologies in their heyday. These firms did so as they mistakenly (in retrospect) believed that they could continue to dominate the market indefinitely and constantly enjoy monopoly rents. Unfortunately, their monopolies ended in the 1980s and their investment in basic research quickly dwindled. However, the role these companies played in basic research was soon replaced by government agencies, notably NIH in biotechnologies and DARPA in digital technologies. The US experience demonstrates that government investment and intervention helped fill the gap left by market participants and prevented potential conflicts of interest among those monopoly giants.

Contrary to Schumpeter's theory, Kenneth Arrow contended in a seminal paper in 1962 that a market with perfect competition was more conducive to innovation. Arrow reasoned that market domination by a small number of companies would create high barriers to entry, which makes startups less likely to succeed and undermines SMEs' motivation to innovate. Although monopoly firms may also innovate, their motivation is undermined by the fact that innovation is disruptive to existing products and processes. Even incremental innovation, such as changes to existing standard processes, means higher costs and greater disruption to monopoly firms. Moreover, monopoly firms may reduce output to raise prices and earn more profits. Lower output means a higher unit cost of innovation, which erodes the whole society's incentives to innovate.

What should be the proper relationship between innovation and monopoly? Ideally, companies in the market should differ in size, operating goals, and business strategies so that the market power gained from innovation would face potential competition. Under these circumstances, the relationship between monopoly and competition would evolve dynamically, providing the economy with new impetus for innovation. As "perfect competition", or a perfectly competitive market, exists only in economics textbooks, our primary concern should be inadequate competition rather than excessive competition. In a nutshell, we believe encouraging competition is conducive to innovation.

The growing digital economy has changed the dynamic relationship between monopoly and competition, posing new challenges in identifying monopolies and formulating policy responses. Generally speaking, we can identify and assess a monopoly by examining three indicators: Firstly, fairness of consumer prices, especially the margin between prices and costs; secondly, availability of alternative products or services for market participants; and thirdly, hurdles to innovation. Traditionally, antitrust policies have focused on prices and market concentration ratios rather than innovation activity, since competition takes place in markets and prices are a clear metric for measuring consumer welfare. However, the traditional approach is confronted with problems caused by changing market structures. For example, some services offered by platform companies are free of charge, and many people do not view them as part of the market. This has made it quite difficult to identify possible monopolies.

As innovation is perceived as the ultimate source of consumer welfare in the long run, we believe innovation activeness[1] is perhaps a more appropriate barometer for determining whether an entity is a monopoly and for identifying the proper policy response. Platform companies extensively engage in innovative activities and they to some extent took off thanks to innovation. The key concern of policymaking is to evaluate whether they hinder the innovation of other companies, especially startups. Are there any exclusivity clauses? Does their acquisition of startups reduce competitiveness (measured by the number of potential competitors)? These are clearly important criteria but not without controversy. For instance, the ex ante identification of competitiveness of potential competitors is problematic as it is quite difficult to predict whether a company currently outside of the market would become a new entrant in the future.

This brings up the question of whether ex ante regulation of ex post resolution can be more conducive to innovation in the context of antitrust measures aimed at platform companies. Both options have risks—preemptive action (ex ante regulation) may stifle growing companies or turn them into public service providers, while ex post antitrust actions against existing monopolies may incur high costs. Thanks to relatively lenient regulations in the past, China's platform companies have grown rapidly, and many of them have become internationally leading firms. However, their large size and extensive business scope have triggered concerns about monopolies. We believe the recent antitrust actions by regulators are conducive to competition despite their impact on the capital market. China's digital economy is already sizable, and we believe the recent impact of antitrust policies may amount to nothing more than minor fluctuations. Considering the benefits that internet platforms can provide to the whole economy, we believe strengthening regulations now is better than stifling platform companies from the beginning which could have smothered these firms in their infancy.

In conclusion, fostering innovation should be a crucial objective of antitrust mechanisms in the new era. For large firms with strong market power, minimum requirements on R&D spending should be established. Digital governance should also be improved so that data becomes an instrument for creating value rather than generating monopoly rents. More importantly, regulators need to support startups and SMEs to encourage competition and foster innovation. Recent policy initiatives have

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[1] This refers to the degree to which innovation is pursued.

emphasized the growth of "specialized, refined, distinctive, and innovative" SMEs, with a key focus on nurturing their innovation capabilities. Enabling SMEs to participate in the division of labor and competition within the global industrial chain is another important aspect of this endeavor. The international competition landscape is also changing, therefore, in addition to efficiency and costs, attention is increasingly drawn to the stability and security of the industry chain.

Enhance the Security of Industry Chains Through Innovation and Opening-Up

Over the past three decades, China and the US have played pivotal roles in global technological innovation and productivity growth. In this so-called "G-2" innovation framework, the US is a frontrunner in key technological advances due to its superior strength in invention and radical innovation. Meanwhile, China's competitive advantage lies in its enormous market as well as its strong production capacity, which has allowed for cost reduction and an increase in global supply capacity via rapid commercialization of new technologies. Consumers around the world have benefited from this innovation framework.

China has managed to narrow the gap with the technological frontier through competition in the international arena and participation in upstream and downstream global industry chains. Meanwhile, demand from China has also financed US companies, which allows them to maintain their innovation capabilities and technological leadership. Other economies have also improved efficiency through specialization in global industry chains. Among them, some small economies have focused on niche segments of the value chain and have become key suppliers of some specialized products globally.

It is worth noting that the G-2 innovation framework faces challenges as the global industry chain is under severe strain from the COVID-19 pandemic, digital governance, and technological competition driven by geopolitics. These impacts have exposed critical vulnerabilities of the global industry chain—i.e., high complexity, low transparency, and poor stability. These problems to some extent are caused by efficiency enhancement measures implemented in recent years along the value chain, including professional specialization and competition, cost optimization, as well as the application of digital and big-data technologies. A clear sign of instability is the rising concentration ratio in different segments of the global industry chain, which exacerbated supply bottlenecks when the shocks occurred.

The weakening impact of the COVID-19 pandemic on the industry chain is evident on both the demand and supply sides. Social distancing and quarantine measures have led to business shutdowns. Instability has increased in transportation and logistics, especially international shipping and air transportation. Moreover, demand has surged in certain regions and sectors (e.g., medical supplies for COVID-19), but has declined or vanished completely in other sectors (e.g., tourism and restaurants). As a result, companies have to be able to cope with changing demand, limited supply, and regional mismatches between demand and supply.

At the same time, international technological cooperation and competition have been increasingly influenced by geopolitics. For example, the US government has issued more administrative measures in its industrial policies. The U.S. Department of Defense, Department of the Treasury, and particularly the Department of Commerce, have imposed restrictions on exports and/or imports by issuing the Entity Lists. As a result, the external environment has changed dramatically for China's technology and hardware industries, especially for semiconductors. In a broader sense, we have seen signs of a resurgence of industrial policies in developed economies. These government policies on industrial development and competition will yield major implications for the evolution of the global industry chain.

How should China respond to the changing domestic and international environment? Ensuring the security of industry chains essentially hinges on technological advancement. The industry chapters focus on three key areas—digital, green, and biotech. China has made significant progress in digital technologies, but still lags far behind frontrunners in a number of key areas. In green industries, China has gained some competitive advantages in photovoltaics and power batteries, but does not have a clear advantage in other strategically important segments such as energy storage and hydrogen energy. In biotechnology, there's ample room for improvement. These three areas intersect with each other and are worthy of discussion. In particular, the application of big data and digital technologies helps catalyze the development of green and biological technologies.

Improving the security of China's industry chains also calls for further opening-up. China promotes scientific and technological progress by participating in and learning from the global market competition, which consists of both "go-global" and "bring-in", especially by attracting talents from abroad. First, In the tripartite structure (i.e., Asia, Europe, and North America) of global value chains, China is a key player in the Asia-Pacific region. Strengthening cooperation with other economies in this region will not only help boost regional development but also reinforce China's essential role in the global industry chain.

Second, enhancing effective information exchange along various segments of the industry chain can help companies better respond to demand-side and supply-side shocks. The digital economy also empowers companies to better participate in the global industry chain and compete in the international arena. The government should improve digital governance and infrastructure, encourage cross-border e-commerce, and ensure the security of data transfer. In the software sector, China should embrace the development of open-source software and expand the scope of applications. We believe these could contribute to independent innovation, facilitating China's transition from catching up to a leading position.

Benefits of Scale Effects

In the new competitive landscape, China's large population and market size are important advantages, and the growing digital economy further amplifies economies of scale and scope. Around the world, the US has to strike a balance between the risk of losing key markets and its goals in geopolitics and international competition. In our view, having more stringent export restrictions in the near term would be more detrimental to the US's technological leadership in the long run. China should leverage its scale effects from both the demand and supply sides to foster innovation and enhance the security and competitiveness of industry chains.

How should we understand China's competitive advantages brought by the economies of scale and scope? Low-cost labor (supply), exports (demand), and favorable industrial policies are usually regarded as key drivers of China's economic miracle and the strong growth of its manufacturing industries over the past few decades. However, we believe that innovation has also played an important role, and exhibited scale effects on both the supply and demand sides, which helps bring down costs. One manifestation is that leadership in China's domestic market share often translates to a prominent position in the global market share. Another manifestation is that China's manufacturing sector has experienced rapid growth in areas with high automation (i.e., not labor-intensive areas) and little government support.

On the supply side, China's advantages include relatively complete industry chains, in-depth participation in the international division of labor, extensive and diversified mutual learning in the corporate sector, as well as technology spillover along the supply chain. Compared to smaller economies, China's manufacturing industry can meet much more diverse needs and serve a wider variety of clients. Coupled with its solid infrastructure and logistics systems, China's manufacturing industry provides fundamental support for innovation in the whole economy. In recent years, a few advanced economies recognized the importance of manufacturing industries and have called for their relocation back home. However, these attempts have hit obstacles such as high relocation costs, sunk costs of past investment, and problems in infrastructure and labor skills. China also faces critical technological hurdles in key areas, which necessitate more independent innovation to explore technological frontiers and achieve breakthroughs.

On the demand side, China's immense domestic market is no doubt a competitive advantage. As demand drives supply, an endogenous driving force for innovation is to identify problems in demand and seek proper solutions. There are three aspects of scale and scope economies worth noting. First, the level of goods consumption in China is already close to the level in the US. We expect robust economic growth to further expand China's consumer market. Second, policy measures to achieve common prosperity will likely reduce income disparities, raise the consumption-to-GDP ratio, and boost mass consumption. We believe the remarkable diversity of consumer preferences brought by mass consumption will in turn fuel innovation. Compared to exports, a key characteristic of domestic consumption is the proximity between consumers (demand) and producers (supply), which should stimulate domestic innovation. Third, with the trend of integrating manufacturing and services, hardware (such as smartphones) often serves as a conduit for providing services. Manufacturers are looking beyond the emphasis solely on quality, technology, and skills, and are also paying more attention to customization, agility, the combination of technology and business models, and the ability to constantly acquire new skills and knowledge. These changes imply that China, as a populous country with an upper middle-income economy, will have a large-scale and diverse consumer demand as a new driving force for technological advancement.

To effectively promote innovation by leveraging China's competitive advantage on the demand side, the key is to ensure sufficient competition in the market. Given the service sector's lower transparency and higher business heterogeneity compared to that of the manufacturing sector, we believe it is especially important to have public policies to manage the relationship between monopoly and competition in the service sector. Transforming domestic demand into innovation drivers would impose new requirements on financing. Therefore, financial support for innovation is more important than trade surplus, FDI, and management of financial resources in the supply chain.

Financial Support for Innovation: Joint Efforts of Capital Markets and Policy-Based Finance

Innovation is an economic activity that needs funding, especially external financing when internal funding is insufficient. Joseph Schumpeter linked innovation with bank credit, asserting that credit is essential to innovation as it creates purchasing power and transfers it to entrepreneurs. The contemporary financial system is much more complex than bank credit in the past, with different countries having varying financial structures. Some lean towards a bank-centric system, such as in Europe, while others lean towards capital markets, particularly equity financing, such as in the United States. What type of financial system is suitable for supporting innovation in China?

Given the high risks and uncertainties in innovation, we believe equity financing is better than debt financing for innovation, as fixed-income instruments are unlikely to generate adequate returns to compensate for high risks. The US's equity markets have greater depth and scope than those of other economies. The Nasdaq market, in particular, has played a crucial role in financing technological innovation in the US. Venture capital investment in digital and biotechnologies has not only fueled innovation but also yielded substantial returns. China's progress in the internet and biotechnology industries has also benefited from the business model of US venture capital firms. Many investors in Chinese unicorn companies follow the US business model, and these companies are often listed in the US equity market, forming the China Concepts Stock.

In recent years, China has launched several reforms to develop multi-layered capital markets and improve their capacity to support innovation. Reform initiatives include the establishment of the Science and Technology Innovation Board ("STAR Market") at the Shanghai Stock Exchange in 2019, the introduction of the pilot registration-based IPO system in the STAR Market in 2019 and in the ChiNext Board of the Shenzhen Stock Exchange in 2020, and more recently, further reforms to the New Third Board (National Equities Exchange and Quotations), and the launch of the Beijing Stock Exchange. Innovation companies listed in both China and the US have been trading at high valuations as the "animal spirits" and herd behavior of market participants often lead to irrational exuberance—i.e., stretched valuations and excessive optimism without support from company fundamentals. In fact, most revolutionary technologies that fundamentally changed the world, such as railways, electricity, computers, and the internet, have given rise to asset bubbles. To ensure that capital markets effectively support innovation, regulators should rein in financial speculation, require adequate information disclosure, and enforce effective investor protection so that capital markets provide long-term financing for R&D and capex in the real economy.

However, the support that equity financing can provide to innovation has limitations as it takes a long time for R&D investment to pay off. The longest payback period expected by venture capitalists (including angel investors) is typically no longer than 5–7 years. Open-market investors are even less patient. However, investors may have to wait 15–20 years before a newly started revolutionary R&D project begins to generate commercial returns. Therefore, some public market investors even hold negative views on listed companies' expenditures on challenging R&D projects. For example, investors' pursuit of short-term returns has undermined the research in groundbreaking new medicines around the world. The clean energy sector is also confronted with challenges from the mismatch between long investment payback periods and venture capitalists' demand for early exits.

On the demand side, companies (depending on size) tend to choose from different sources of finance to suit their levels of risk tolerance. Most startups and small companies rely on equity financing, especially venture capital and angel investment, while large companies prefer relying on bank credit and cash flows from their own business revenue. The best hedge against uncertainty is self-insurance, as large companies usually earn relatively high profits or have established long-term relationships with banks, but small companies are less able to manage cash flows effectively.

The government plays a unique role in facilitating financial support for innovation as it can spread the risks of innovation across the society and reallocate risks among different generations. For example, the government may arrange debt-financing for innovative firms and projects, including government guarantees for loans and project financing by policy-based financial institutions. The government may also encourage banks to increase lending to technological innovation projects and advanced manufacturing. In fact, supporting and serving the national development strategies and the real economy are listed at the top of the four main goals assigned to commercial banks in the new version of the Performance Evaluation Framework for Commercial Banks issued by China's Ministry of Finance. Another approach is the usage of "guidance funds" for investment in specified industries. For example, China's Ministry of

Finance and the Ministry of Industry and Information Technology jointly guided the launch of an investment fund for the semiconductor chip industry.

From a broader perspective, we think that the rapid growth of consumer finance and the real estate industry not only enlarged financial risks but also undermined the support of finance for innovation and investment in the real economy. With effective rules and regulations implemented since the National Financial Work Conference in 2017, China has made remarkable progress in the governance of non-compliant financial activities. Looking ahead, we believe operations of different business lines of financial institutions should remain separated from each other, and compliance requirements in the banking industry should be strictly enforced. Moreover, China could develop policy-based financial institutions, and encourage equity financing, while avoiding excessive financialization.

From Technological Innovation to Common Prosperity

This book explores what mechanisms and ecosystems are conducive to innovation. In essence, we highlight how changes in production affect productive forces, and how productive forces fundamentally determine relations of production by changing modes of production, lifestyles, as well as social relations. For example, digital technologies and relevant applications not only affect the economy, but also influence society, politics, and culture. Public policies play two complementary roles: Fostering innovation and coping with subsequent economic or social impacts.

Two key issues warrant further analysis from a macro perspective. The first issue is the impact of innovation on economic cycles. Technological advancement is often associated with Kondratieff waves—i.e., long-term cycles driven by waves of technological progress. A typical Kondratieff cycle may last 50–60 years. Since the Industrial Revolution, the world has experienced five such waves. The digital revolution (e.g., software, data, and the internet) is the latest wave, while green technologies may be the next. Given investors' "animal spirits" in decision-making, innovation may also affect short- and medium-term economic cycles. A particularly noteworthy issue is that the resource reallocation brought by technological innovation may accelerate the downside corrections in the second half of China's financial cycle. This may create headwinds in the overly expanded real estate and related sectors, and accentuate the importance of the prevention and mitigation of debt risks.

The second issue that needs further analysis is innovation's role in boosting inclusive growth. At the tenth meeting of the Central Committee for Financial and Economic Affairs, Chinese policymakers emphasized the importance of common prosperity amid high-quality development, and encouraged people to achieve prosperity through innovation and hard work. Innovation should be fairly priced as it needs capital investment and requires sufficient returns to attract entrepreneurs and technology professionals. An important perspective to the analysis of income distribution is the relationship between labor and capital. Over the past few decades, mainstream neoclassical economists have perceived technological advancement and the labor market as two separate issues. On the contrary, classical economists (e.g., Adam Smith and David Ricardo) and Karl Marx analyzed how wages and return on capital are affected by the use of machines (innovation). However, how will innovation affect the labor market structure as well as the protection of labor rights in the new era? This is an important aspect of primary income distribution.

Innovation is a collective activity, but the range of beneficiaries of innovation's returns seems much smaller than that of risk-bearers. Since government investment in innovation has helped spread the risks across the society, this inevitably raises the question of how and to what extent can the benefits of innovation be shared. For example, some have argued that Silicon Valley firms have privatized benefits that should have been shared with the public since it was the US government that funded the initial creation of the internet. Should public investment in innovative firms be transformed into equity stakes and enjoy the same rights as private investment? A possible answer is provided by the innovation and industrial funds supported by the Chinese government. In our view, the key to the social sharing of innovation benefits is to establish a sound governance mechanism that ensures ordinary people can benefit from public investment in innovation. This is also an important issue in primary income distribution.

Social sharing of innovation benefits can also be achieved through secondary income distribution by fiscal measures and taxation such as capital gains tax. Should China introduce a capital gains tax? Compared to transforming public investment into an equity stake in the funded company, would a capital gains tax impede innovation? The US's experience suggests that capital gains tax has not hindered, but has been conducive to innovation, as it discourages short-term activities and encourages long-term investment.

In conclusion, technological innovations are a key driving force of China's high-quality development. Fostering innovations is a systematic quest that requires an effective ecosystem supported by an efficient market and a capable government. CICC Research and the CICC Global Institute are committed to providing in-depth analysis of major topics about China's economic development. This book on technological innovation represents another joint achievement of CICC Research and the CICC Global Institute, following the publication of *Digital Economy: The Next Decade* (2020) and *Guidebook to Carbon Neutrality in China* (2022). We hope this book will facilitate a better understanding and further discussion of innovation-related issues.

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This book is written based on the report “Technological Innovation and Industrial Value Chain Development”, originally in Chinese (创新: 不灭的火炬) and published in 2021. The book analyzes China’s innovation economy by examining the current state of innovation, existing and potential challenges, and possible policy implications. The previous report had 18 chapters and over 500 pages, which was then condensed and reorganized into the current form, with seven chapters focusing on major themes and core issues. The book, we believe, is a concise, coherent, and engaging narrative that will guide interested readers through the sometimes overlooked, yet tremendously important subject of the development of the innovation economy as an engine of growth and social progress in China.

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Preface: Unquenchable Flames: The rise of China's innovation economy

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Chapter 1 Technological innovation in China: Current state and challenges

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Chapter 7 Supporting innovation: Unquenchable flames

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Introduction

CICC Research was founded upon the establishment of China International Capital Corporation (CICC), which is renowned for its emphasis on research. It was the first in China to establish a sell-side research framework, conducting research based on fundamental analysis and creating a cross-border research model of "One Team, Global Market". With its extensive coverage, rigorous research methods, objective approach, and insightful forward-looking perspectives, CICC Research has positioned itself among the most influential research institutions and has garnered the reputation of being "Chinese experts" among its clients.

CICC Global Institute (CGI), established in November 2020, is positioned as a new form of high-level think tank that is oriented to serving public policy research and decision-making. It focuses on economic and financial research, striving to understand economic and industry trends and to establish a platform for communication between China and the world. CGI and CICC Research possess different sets of focuses and strengths, collaborating in their efforts to support China's national strategy and to enhance CICC's business performance and development.

Contents

Chapter 1
Technological Innovation in China: Current State and Challenges

Abstract Technological progress and the substantial easing of international competition after the Cold War have jointly shaped the pattern of division of labor in the international industry chain over the past few decades. While serial production and network collaboration have improved production efficiency, industry chain security has gradually become a cause for concern. We believe the policy response should focus on enhancing irreplaceability domestically to address risks from international competition as countries deemed irreplaceable in the industry chain could resume production by establishing new network connections with other production partners, while countries that are less irreplaceable are at risk of being marginalized or even removed from the production network.

According to our analysis of the global value chain, China as a whole is in the downstream. In our view, on one hand, China's advantages mainly lie in low-tech manufacturing industries, exposing the country to potential horizontal risks posed by trade frictions for the purpose of decentralization. On the other hand, China's disadvantages mainly lie in primary products such as oil and medium- and high-tech industries such as software, exposing the country to potential vertical risks posed by overseas supply bans.

The key to coping with horizontal and vertical risks lies in technological progress. To clarify the future path of innovation, we believe it is crucial to examine the current state of China's technological innovation and understand its major challenges. We take the perspective of a country's innovation system to assess the status quo of China's innovation activity. Regarding innovation input, China ranks only behind the US in terms of R&D spending, but still lags behind the world's technology powerhouses in terms of R&D intensity. We think the country still needs to enhance its R&D intensity, especially in basic research that is vital for radical innovation. Talent is another crucial driver of innovation. China has a large talent base, but we believe there is room for improvement in the number of researchers per thousand people in the labor force as well as the quality of labor and structure of human capital. We believe the supply-side challenges constraining the education system and hindering the cultivation of innovators are three-fold: Uneven distribution of high-quality basic education resources, the intensified incentive system in exam-oriented education, and educational administration factors in research-oriented universities.

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In terms of technological outputs, we focus on academic publications and commercial patent applications to measure China's achievements in knowledge innovation. We compare the 30-year history of China's knowledge innovation with international experience and highlight five patterns. First, as a latecomer to knowledge innovation, China has caught up with developed countries in terms of quantity, and the gap between China and developed countries in terms of quality is narrowing. Second, China's contribution of core innovation to global output remains limited and it lags behind developed countries in terms of originality. Third, from the perspective of conversion of achievements in knowledge innovation, industries do a good job while conversion of academic research results is relatively weak. Fourth, China tends to post strong performance (in knowledge innovation) in areas in which it has comparative advantages in international trade. Fifth, the growth momentum of China's cooperation with foreign entities in knowledge innovation has slowed in recent years, especially in the field of academic cooperation, which deviates from the global trend.

Having examined China's current position in the global value chain as well as its innovation inputs and performance, we use criteria of "systemic importance" and "promising development prospects" to identify three major areas for further analysis: The digital economy, the green economy, and the bioeconomy. We note that regardless of international competition, China still needs to increase R&D intensity and accelerate technological progress to achieve its medium- and long-term growth targets. Regardless of the perspective of either international competition or domestic growth, China needs to accelerate technological progress, in our view, and policy intervention is indispensable to accelerating technological innovation.

In this book, we discuss the paths to accelerating technological innovation in two parts. Three macro chapters focus on the analysis of innovation economics including the status quo (this chapter), the scale effect (Chap. 2), and the innovation ecosystem (Chap. 7). We also include four industry-focused chapters, which examine the application of innovation economics in digital industries (Chap. 3), green energy (Chap. 4), the biotech industries (Chap. 5), and supporting industries such as manufacturing and logistics (Chap. 6).

1.1 Innovation in the Era of Heightened International Competition

With technological advancements in manufacturing and logistics, product trade has gradually evolved into industry chain trade. From our perspective, while division of labor in the industry chain has improved efficiency, the increase in segments has made the entire industry chain and the economy more vulnerable. The COVID-19 pandemic has accelerated the exposure of this problem,[1] prompting countries to begin paying close attention to industry chain security. For China, the industry chain risks emerged earlier—trade frictions in 2018 underscored the importance of industry

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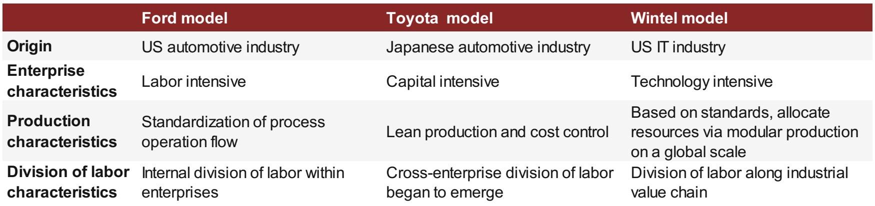
[1] Vertical risk comes from the supply constraints in the midstream and upstream of the supply chain.



	Ford model	Toyota model	Wintel model
Origin	US automotive industry	Japanese automotive industry	US IT industry
Enterprise characteristics	Labor intensive	Capital intensive	Technology intensive
Production characteristics	Standardization of process operation flow	Lean production and cost control	Based on standards, allocate resources via modular production on a global scale
Division of labor characteristics	Internal division of labor within enterprises	Cross-enterprise division of labor began to emerge	Division of labor along industrial value chain

Fig. 1.1 Evolution of manufacturing production models. *Source* Wintel model: micro basis of US new economy and global industrial restructuring (Huang Weiping et al. 2004), CICC Global Institute

chain security. Regarding how to ensure industry chain security, countries seem to have reached a macro-level consensus that it is necessary to shorten the industry chain and increase local production capacity, gaining security at the cost of a certain loss in efficiency.

According to this macro point of view, efficiency and security cannot be achieved at the same time. However, from a micro perspective, we believe an important basis for the industry chain division of labor is the Wintel model.[2] This production model breaks up a production process originally within a single company into steps carried out in different companies, regions or even countries, so as to form new divisions of labor and new production systems. Economist Masahiko Aoki, professor emeritus both at Stanford University in the US and at Kyoto University in Japan, studied the US's new economy and concluded that the US relied on new forms of industrial organization represented by the Wintel model to reverse the competitive disadvantages of US companies against Japanese companies, and achieve sustained rapid economic growth in the mid to late 1990s[3] (Fig. 1.1).

However, for industries characterized by the Wintel model, the irreplaceability of each segment in the industry chain varies. R&D is at the core of the industry chain and is the most irreplaceable segment. A company can take a dominant position to a great extent along the entire value chain if it dominates upstream R&D. Other segments with lower irreplaceability provide production support for the core segment and are subordinate to it. Judging from the Wintel model at the micro level, the key to improving industry chain security is to increase one's irreplaceability. In our opinion, this means that efficiency and security can be achieved at the same time, and the key lies in strengthening R&D and technological innovation.

The problem is that the above two perspectives derive different views of the relationship between efficiency and security of the industry chain. Hence, we will explore and assess these differences in this chapter.

The essence of industry chain security is high irreplaceability. Theoretically speaking, industry chain division of labor can take place both domestically and internationally, so the security of the industry chain can also be discussed from the perspectives of domestic production and international trade. In reality, concerns about

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[2] Windows-Intel model.

[3] Aoki M., Andoh, H. (2002) Modularity: A New Industrial Architecture.

Fig. 1.2 China's domestic discussion on industry chain security. *Note* CNKI stands for China National Knowledge Infrastructure. *Source* cnki.net, Wind Info, CICC Global Institute

industry chain security mainly arise from the perspective of international trade. In June 2021, the White House stated in its supply chain security review report that concerns about industry chain security stem from a reliance on foreign sources of raw materials and foreign manufacturing production.[4] Similarly, in China, discussions on this topic have been on the rise, with the number of papers on the topic of industry chain security being also highly related to the volume of China's exports and imports (Fig. 1.2). Therefore, we also discuss industry chain security from the perspective of international trade.

1.1.1 Characteristics of Global Industry Chain: Serial Production and International Collaboration

The global industry chain has formed a complex production structure characterized by serial production and international collaboration. Comparing recent global trade flows with those 20 years ago, we find various economies are increasingly involved in the global trade division of labor, and the global trade network has become increasingly complex. During this process, China has replaced Japan as the Asian center of the global trade network (Fig. 1.3).

The characteristics of this industrial division of labor are jointly shaped by technological progress and thawing of international relations. In terms of technological progress, the most important changes are a decline in logistics costs and the adoption of new manufacturing models, notably the Wintel model. The decline in logistics costs makes global resource allocation and cross-border collaborative production possible. The Wintel model makes cross-enterprise serial production a common production model in technology-intensive industries. Under the influence of these

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[4] White House (2021) 100-Day reviews under executive order 14,017.

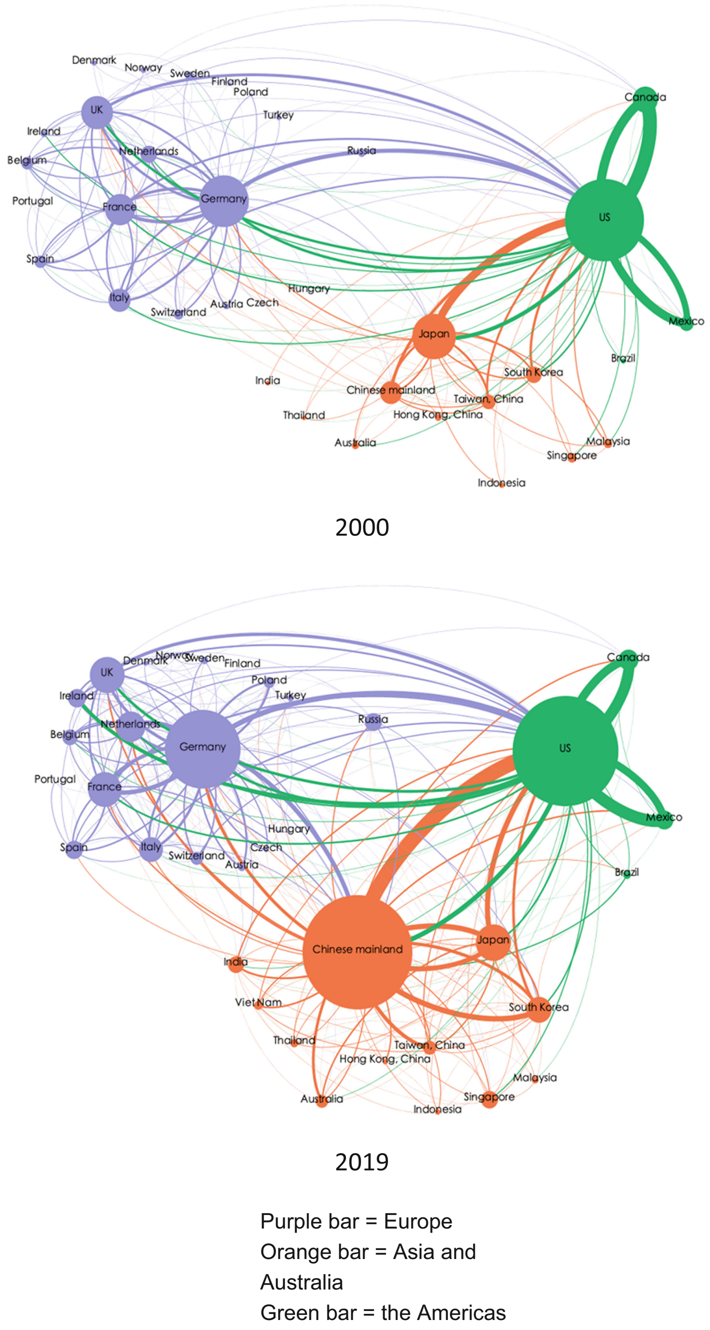

Fig. 1.3 Global trade flows. *Note* The chart shows bilateral trade of more than US$5bn (measured in 2000 constant US dollars). Any curve represents the export of goods from the upstream node to the downstream node in a clockwise direction. The size of the node represents the total export value of the economy, and the thickness of the curve represents the size of the bilateral trade volume. The color of the curve is the same as the color of the exporting country. *Source* Gross Trade Accounting: Official Trade Statistics and Measurement of Global Value Chains (Wang Zhi et al. 2015), ADB MRIO database, CICC Global Institute

two factors, the division of labor of the global industry chain has become increasingly sophisticated, and the global value chain has continued to lengthen.

In terms of international relations, the easing of geopolitical conflicts after World War II (especially after the Cold War) created a favorable international environment for the signing of trade agreements, which greatly lowered tariff levels worldwide and reduced the cost of cross-border flows of goods. The connection of different regional markets has created globally integrated new product and labor markets, promoting the global industrial division of labor. In particular, China's accession to the World Trade Organization (WTO) in 2001 has profoundly changed the global and regional trade landscapes as well as division of labor, and the network-based production featuring collaboration between countries has become increasingly complex.

1.1.2 Sources of Industry Chain Risk and the Nature of Security

As the division of labor becomes increasingly sophisticated, the industry chain also faces various risks. The Biden Administration states that sources of industry chain risk include global pandemics, cyberattacks, climate shocks and extreme weather, terrorist attacks, geopolitical and economic competition, and other factors that will erode the US's key manufacturing capabilities and impact the availability and integrity of critical goods, products, and services.[5] In summary, industry chain risks can be divided into two categories.

First, natural disasters impact serial production, and disruption of any segment will make it difficult to complete the entire production process. For example, in March 2011, a magnitude 9.0 earthquake in northeastern Japan caused many wafer fabs to reduce production or even shut down, triggering a global integrated circuit sales price increase of about 8% MoM and a flash memory price increase of nearly 25% MoM.

Second, international competition disrupts network collaboration, forcing a country's production nodes to reconnect with other nodes, and the international collaboration network is artificially impacted so that production efficiency decreases. Upon the introduction of trade barriers, technology blockades, and trade bans on raw materials between countries originally in a collaborative relationship, the original production model of the industry chain could be severely impacted. This risk is particularly prominent against the background of rivalry between major powers, in our opinion.

Compared with natural disasters, we believe risks of international competition deserve more attention, for the following reasons. First, natural disasters usually do not last long. For example, the impact of the Japanese earthquake in March 2011 on semiconductor prices largely subsided after the end of the month. In contrast, major international competition usually lasts longer. Second, under the impact of natural

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[5] White House (2021) 100-Day reviews under executive order 14,017.

disasters, the duration of the impact and the degree of damage can be minimized through close cooperation between countries. In contrast, international competition alone is enough to disrupt the entire industry chain even if there is no natural disaster.

For industry chain risks caused by international competition, there are no apparent winners in the short term as no one can complete serial production without cooperation from others. However, in the medium and long term, the impact on different segments varies: On the one hand, the irreplaceability of each segment in the industry chain is different. On the other hand, the division of labor in the industry chain is characterized both by serial production and by network collaboration. Countries in highly irreplaceable segments are capable of resuming production by gradually establishing new connections with other production nodes. However, countries in less irreplaceable segments may be gradually marginalized by the industry chain, and may even be removed from the industry chain and be unable to resume production for a long time.

Since the occurrence of industry chain risks is unavoidable and even unpredictable, we focus on the resumption of normal production after risks occur. In other words, the nature of industry chain security is not to completely avoid the occurrence of risks, but to effectively cope with the impact of risks. This implies that if we focus on industry chain risks caused by international competition, we need to examine China's irreplaceability in various industry chains. However, questions lie in how to measure a country's irreplaceability, to identify China's competitive and uncompetitive industries, and those facing different industry chain risks.

1.1.2.1 Decentralization: Low-Tech Industries Face Horizontal Risks

Since joining the WTO, China has grown into the world's largest exporter over the past two decades. However, a breakdown of China's exports into primary products, low-tech manufacturing industries, and medium- and high-tech manufacturing industries,[6] as depicted by the revealed comparative advantage (RCA) index[7] (a relative indicator) and the export share[8] (an absolute indicator) shows China's current advantages mainly lie in low-tech manufacturing industries. In 2019, China's RCA indexes for primary products, low-tech manufacturing industries, and medium- and high-tech manufacturing industries were 0.22, 1.27, and 1.11; and China's shares of global exports for the three categories of industries were 3%, 17.4%, and 15.3%.

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[6] We refer to the ADB MRIO database for classification standards of the three categories of industries. Primary product industries are mainly agriculture and mining. Low-tech manufacturing industries are mainly primary product processing, textile and apparel. High-tech manufacturing industries are mainly equipment manufacturing.

[7] RCA index below 1 means the industry has a comparative disadvantage. RCA index above 1 means the industry has a comparative advantage. RCA index above 1.25 means the industry has a strong comparative advantage.

[8] Note: Export share = the country's export value of the category of goods divided by global export value of the category of goods.

We take a further look at the RCA indexes of 97 industries classified by two-digit HS codes. Among the 18 primary product industries, China's RCA index was above 1 for eight industries in 2000, but for only three industries in 2019. Among the 58 low-tech manufacturing industries, China's RCA index was above 2.5 for 16 industries and above 1 for 34 industries in 2019, pointing to China's strong comparative advantages in low-tech manufacturing industries. Among the 21 medium- and high-tech manufacturing industries, China is not very competitive, with its RCA index above 1 for only eight industries in 2019. China has relatively clear comparative advantages in the musical instruments, electrical machinery, appliances and equipment, and electric railway vehicle industries. However, China does not show comparative advantages in the aircraft, pharmaceutical, cosmetics, and automobile industries, and this situation has not improved much in the past two decades.

The export shares of the 97 industries also show China's current advantages mainly lie in low-tech manufacturing industries. Among the 18 primary product industries, China's feather and down products industry had the highest export share at 22% in 2019. Among the 58 low-tech manufacturing industries, China's export share exceeded 20% for 28 industries, and was more than 50% for six industries, and reached about 80% for feather and down products and umbrellas in 2019. Among the 21 medium- and high-tech manufacturing industries, China's export shares in 2019 were not high; the industry with the highest export share was musical instruments (and related parts) at 25%.

In general, China's comparative advantages in export trade are mainly in low-tech manufacturing industries. However, the current comparative advantage does not mean that these industries are risk-free. In fact, we think these industries face horizontal risks caused by deglobalization. As mentioned earlier, China is a central link in global trade of these low-tech manufacturing industries. Therefore, the horizontal risk under trade frictions is decentralization—that is, reduced dependence on China as a central trade node. An important manifestation of horizontal risk is external demand decline and production capacity transfer.

1.1.2.2 China Faces Vertical Risks in Some High-Tech Industries and Primary Products

Although analysis from an export perspective confirms China's central position in global trade of finished products, China's advantages are smaller in trade of intermediate products. In our opinion, the more complex the division of labor for an intermediate product, the smaller China's advantage is in trade. Analysis based on the global value chain position index shows China as a whole is at the end of the global industry chain. The higher the index, the further the country is from end-consumers. Russia and Australia have high indexes because they export raw materials such as minerals and oil & gas resources. Japan and the US have higher indexes because they are in the midstream and upstream links such as R&D. China is in the downstream of the industry chain, and its imports are constrained by countries that export basic resources, key technologies, and key equipment (Fig. 1.4). It is necessary to further analyze China's industry chain risks in light of the degree of dependence on imports.

China accounted for 11.2% of global imports in 2019 and was the world's second-largest importer, only behind the US (14%). China's median share of global imports in the 1,242 industries classified by four-digit HS codes in 2019 was 4%, an increase of 2.2ppt from the level in 2000. Among imports in primary products, low-tech manufacturing industries, and medium- and high-tech manufacturing industries, China had the highest import share for primary products, while the US had the highest import shares for both low-tech manufacturing industries and medium- and high-tech manufacturing industries (Fig. 1.5).

We note that China's overall import share in 2019 was higher than the 75th percentile of its import shares among 1,242 industries (Fig. 1.6). This means that China's import structure is polarized—more than 75% of industries have an import

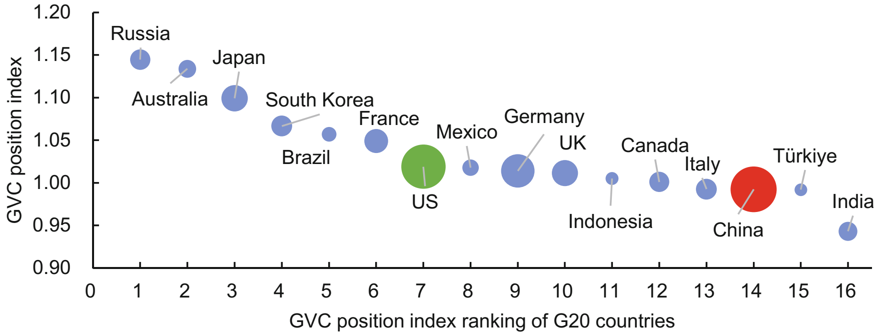
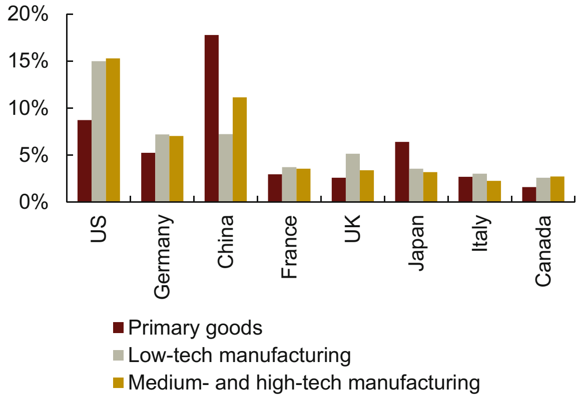


Fig. 1.4 2019 global value chain position index. *Note* The higher the global value chain position index, the closer the country to the upstream of the global value chain. The size of the bubble represents the size of the domestic value added absorbed by foreign countries in the country's total exports. *Source* Gross Trade Accounting: Official Trade Statistics and Measurement of Global Value Chains (Wang Zhi et al. 2015), ADB MRIO database, CICC Global Institute

Fig. 1.5 Import shares of China and G7 countries, 2019. *Note* Import share = the country's import value of the category of goods / global import value of the category of goods. *Source* UN Comtrade, CICC Global Institute



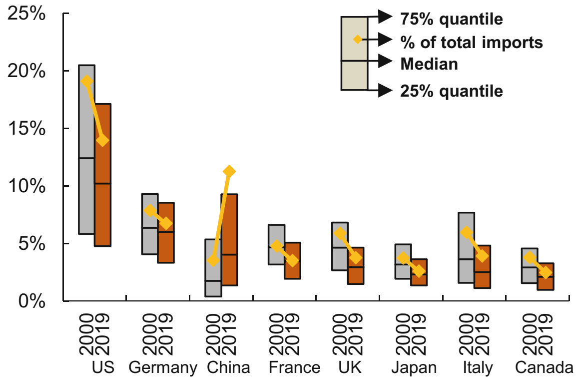


Fig. 1.6 Import share distributions of China and G7 countries by industry. *Note* Import share = the country's import value of the category of goods / global import value of the category of goods. *Source* UN Comtrade, CICC Global Institute

share below average, while the heavy import dependence of a small number of industries significantly increases the overall import dependence.

Our definition of heavy import dependence includes three dimensions—namely import value, share of global imports, and concentration ratio of top-four sources of imports (CR4) (Fig. 1.7). The larger the first two indicators, the higher the dependence of the industry chain is on imports; the higher the third indicator, the higher the dependence on imports from one or a few markets and the more susceptible to international competition or natural disasters. Considering the size of China's economy, we exclude industries with an import value of less than US$2bn from the 1,223 industries classified by four-digit HS codes, and screen industries with high import dependence.

Among China's 207 primary product industries, 24 industries (11.6% of the total) are identified as having high import dependence, especially mineral resources such as petroleum crude oil, iron ore, petroleum gas, copper ore, and oil crops such as soybeans (Fig. 1.8). Some products (such as iron ore, soybeans, and palm oil) have an import source CR4 above 90%.

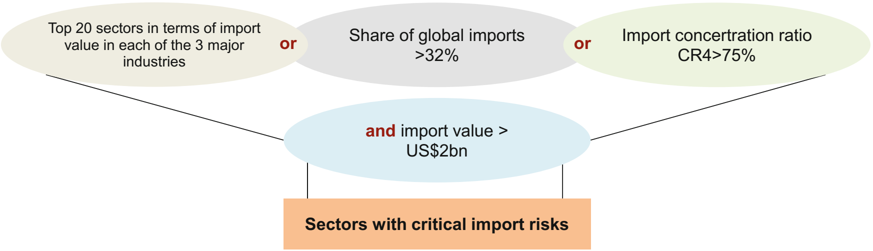


Fig. 1.7 Screening framework for industries with high import dependence. *Note* Screening is based on the 1,223 industries classified by four-digit HS codes. China accounted for 16% of global GDP in 2019, and we consider an import share above 32% (double the GDP share) as high. We refer to the market concentration standards, and an import source CR4 above 75% means that the market is highly oligopolistic. CR4—concentration ratio of top-four sources of imports. *Source* CICC Global Institute

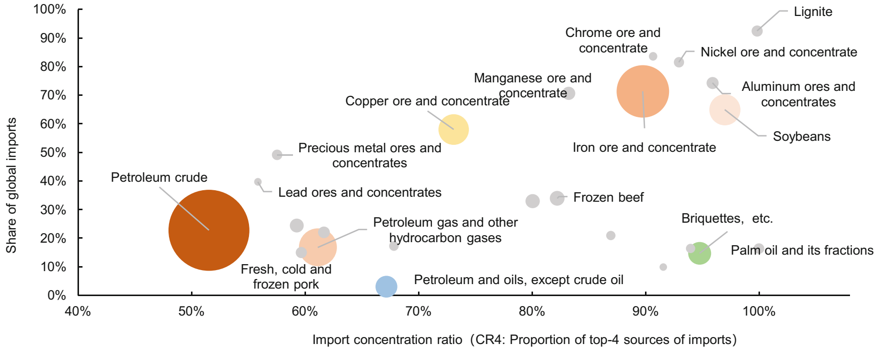


Fig. 1.8 Among primary products, mineral resources and oil crops have heavy import dependence. *Note* The size of the circle represents the value of imports of various products by the Chinese mainland in 2019; import share = the country's import value of the category of goods/global import value of the category of goods, both in 2019. *Source* UN Comtrade, CICC Global Institute

Among the 609 low-tech manufacturing industries, only 35 industries (5.7% of the total) are identified as having high import dependence, mainly rough processing of primary products such as refined copper and copper alloys (Fig. 1.9). These industries are not technologically complex, and their import concentration is relatively low. China is unlikely to be technically constrained by other countries in low-tech manufacturing industries. The more important consideration is ensuring the import security of upstream mineral resources.

To sum up, China's disadvantages lie in primary products such as petroleum, soybeans, and iron ore, as well as medium- and high-tech manufacturing industries

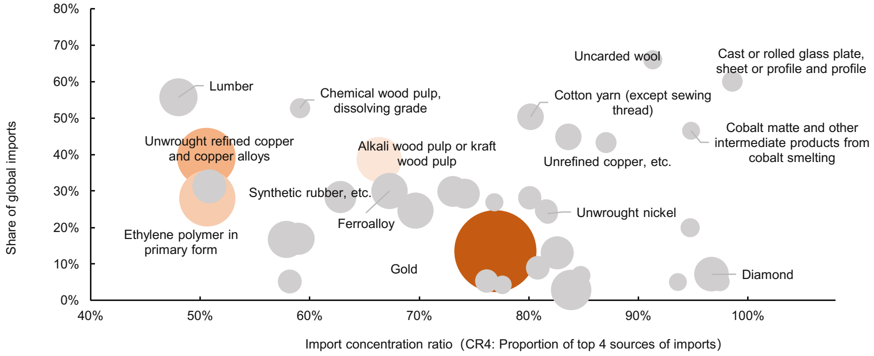


Fig. 1.9 Among low-tech manufacturing industries, primary metal smelting products have heavy import dependence. *Note* The size of the circle represents the value of imports of various products into the Chinese mainland in 2019; import share = the country's import value of the category of goods / global import value of the category of goods, both in 2019. *Source* UN Comtrade, CICC Global Institutem

such as integrated circuits, integrated circuit manufacturing equipment, motor vehicles, and pharmaceuticals. If these industries with high import dependence experience a cutoff in overseas supply, their domestic production could be disrupted. Since such risk comes from the midstream and upstream, it is called "vertical risk."

1.1.3 Technological Innovation: Key to Improving China's Industry Chain Security

In our opinion, the fundamental reason for the low irreplaceability of China lies in insufficient R&D investment. This issue exists not only in high-tech industries, but also in low-tech manufacturing industries where China has advantages. This is a common problem in China's manufacturing sector. The capital intensity is higher than the R&D intensity in almost all of China's industries, and manufacturing companies compete more by expanding production capacity than by increasing R&D (Fig. 1.10). This may cause a waste of resources and excessive competition in low-end industries as well as insufficient R&D investment and weakened incentives for companies to move up the value chain. Therefore, increasing R&D intensity and accelerating technological innovation are not only needed in high-tech industries to enhance value chain security, but in various other industries as well.

Regarding primary products, China relies heavily on imports of important raw materials (such as oil) that pose vertical risks. In general, as primary products are natural resources, the solution to vertical risk includes economic means such as diversifying import sources, building domestic stock, and non-economic means. However, these are only short-term measures with questionable effectiveness. We believe China needs to rely on technological progress in green energy and other areas to solve the problem of heavy import dependence on primary products such as oil.

As mentioned earlier, China is facing horizontal risk caused by deglobalization in low-tech manufacturing industries where it has comparative advantages. We emphasize that although some companies have relocated their production lines to Vietnam, the Philippines, and other countries to avoid tariff issues since 2018, more global companies have adhered to a China-based strategy. This shows trade frictions alone are not enough to change China's comparative advantages. The key horizontal risk lies in technological progress. A study shows that every robot added in the US manufacturing industry replaces 3.3 workers.[9] The widespread use of industrial robots appears to be slowly bringing manufacturing back to the US, and the size of manufacturing investment in the US has increased steadily in the past decade. Against this background, developing countries that rely on demographic dividend to serve as the "world's factories" may face the possibility of export production capacity being substituted. In our opinion, for China to fundamentally eliminate horizontal

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[9] Acemoglu, D., Restrepo, P. (2020). Robots and jobs: evidence from US labor markets. Journal of Political Economy, 128(6), 2188–2244.

Fig. 1.10 China's manufacturing sector has large capital expenditures but insufficient R&D investment. *Note* Data of listed manufacturing companies in the countries in 2020. R&D (capital) intensity = R&D (capital) investment/sales revenue. *Source* Factset, CICC Research Manufacturing Team

risks faced by its low-tech industries, it is vital to enhance irreplaceability through technological progress.

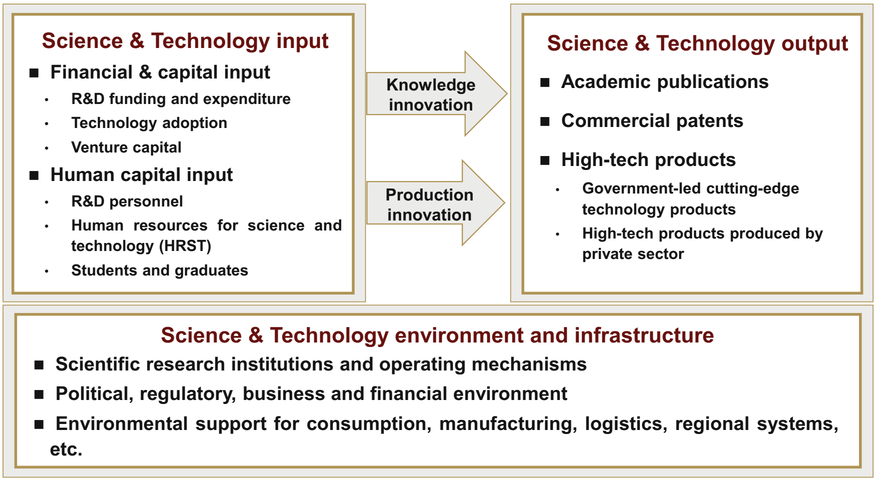

Fig. 1.11 Key indicators in a national science and technology (S&T) innovation system. *Note* Technological innovation mechanism and environment in the figure based on WIPO Global Innovation Index framework. *Source* OECD, CICC Global Institute

1.2 Assessment of Innovation Activity in China: From the Perspective of Innovation System

As previously discussed, we believe the key to strengthening irreplaceability is to improve R&D investment. However, R&D cannot function alone, and innovation activities also need competent researchers and a supportive policy environment. Moving from a global perspective to innovation in China, we seek to provide a full picture of China's innovation status quo based on the structure of its innovation system. The innovation system of a country usually consists of three parts: Technological innovation input, technological innovation environment, and technological innovation output[10] (Fig. 1.11). This section focuses on evaluating the inputs and outputs of technological innovation in China. Innovation inputs include capital investment and human resource investment, of which capital investment features R&D. As discussed in section 1, R&D is at the core of accelerating innovation. It comprises creative and systematic work undertaken in order to increase the stock of knowledge and to devise new applications of available knowledge. Talent is also essential to innovation, and China benefits from its large talent base. Through knowledge and production innovation activities, capital and human resource inputs convert into innovation outputs, including academic publications and patents, among others.

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[10] OECD, (2009). Measuring china's innovation system national specificities and international comparisons.

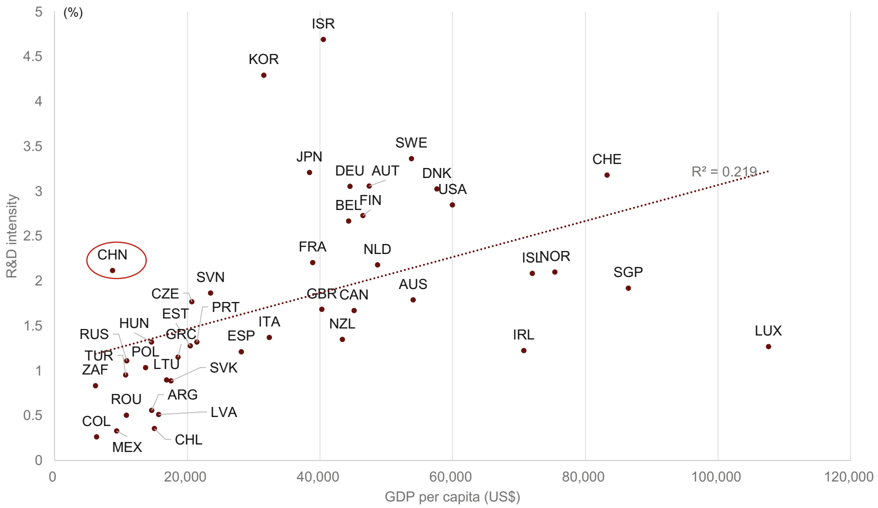

Fig. 1.12 Relationship between R&D intensity and per-capita GDP in sample countries worldwide, 2017. *Note* Per-capita GDP is calculated based on US dollar value in 2017. *Source* OECD, World Bank, CICC Global Institute

1.2.1 Technological Innovation Inputs: R&D Expenditure and Human Resources

1.2.1.1 Is China's R&D Investment Sufficient?

China's R&D investment has increased rapidly since 2000, and currently is the second largest in the world. The country's R&D intensity has also increased year by year and has reached 2.4%, which is close to the average of advanced economies and much higher than the average of developing countries. However, is China's R&D investment large enough?

An important factor that affects R&D intensity is a country's economic performance, which can be measured by per-capita GDP. Data from 43 countries in 2017 indicates that R&D intensity is positively correlated with per-capita GDP (Fig. 1.12). Given China's current per-capita GDP, the country's R&D intensity seems high and is close to the level of many developed economies. As major technology powerhouses' R&D intensity reached 2.23% in 2019, the same level as China's current R&D intensity, their per-capita GDP at least exceeded US$10,000 or even US$20,000. However, China's per-capita GDP is only US$8,342.3 in 2020 (based on constant US dollar in 2010).[11]

We believe that it is imperative for China to increase its R&D intensity in order to achieve long-term economic development targets. In addition, raising R&D intensity has been shown to be an important way for less developed countries to catch up

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[11] Source: Haver Analytics.

with advanced economies. For example, R&D intensity in Japan, South Korea, and northern European countries exceeded that of the US amid their rise, marking a sharp contrast with the low R&D intensity in Latin American countries and other countries in Asia and Europe.[12] We note that China, as a large country that is attempting to catch up with developed economies, is likely to become the first country whose R&D intensity exceeds 3% when its per-capita GDP is less than US$30,000.

However, China faces structural problems in R&D spending. Companies have accounted for an increasingly large proportion of China's R&D sources since 1990. They replaced the government as the largest source of R&D funding in 1997, and their share is now at 76%. In contrast, the government's share of R&D investment trended downward to around 20% in 2013 from the late 1990s. Although companies contribute a large part of China's R&D spending, their R&D intensity remains low and they are reluctant to invest in basic research.

Corporate R&D intensity refers to the ratio of companies' R&D spending to their revenue. We find that a country's R&D intensity exhibits a clear linear correlation with corporate R&D intensity.[13] China's corporate R&D intensity was only slightly above 2% in 2017. We believe this is an important reason why China's overall R&D intensity is still lower than technology powerhouses. The industry of instrument and apparatus is the only one in China that has a corporate R&D intensity over 3%. The R&D intensity is only 2.19% for the computer, communication, and electronics industries, and even lower than China's overall R&D intensity.[14] In contrast, R&D intensity in multiple industries in the UK has exceeded 3%, and it even surpassed 5% in a number of industries in the US.[15]

China's spending on basic research is insufficient, in our opinion. In China, R&D as a percentage of GDP is comparable with that in the US, but the vast majority of R&D investment goes to Development (D)—i.e., the development and promotion of products and technologies—while Research (R) accounts for a much lower proportion in total R&D investment than in the US.

Spending on experimental development as a percentage of China's total R&D spending reached 82.7% in 2018, exceeding that of US, Japan, South Korea, and Israel. However, the share of China's spending on basic research is much lower. In contrast, the share of the spending on basic research is above 10% in the UK, US,

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[12] Fagerberg, J., Godinho, M. M. (2004). Innovation and catching-up. The Oxford handbook of innovation. Oxford university press.

[13] A country's R&D intensity and corporate R&D intensity have no theoretical linear relationships. However, their statistical relationships are clearly linear based on data from OECD. Their calculation formulae indicate that the result of corporate R&D spending/national R&D spending is very close to the result of corporate added value to GDP ratio. This means the share of companies in a country's R&D spending is consistent with the share of industrial added value in the country's GDP. In other words, when industrial economy accounts for a large proportion of a country's total economy, companies have many resources to invest in R&D.

[14] Source: China Science and Technology Statistics.

[15] The data for China is from Wind Info and China Statistical Yearbook on Science and Technology; the data for the UK is from Hughes, K. (1988). The interpretation and measurement of R&D intensity – A note. Research Policy, 17(5), 301–307; the data for the US is from the Census Bureau of US Department of Commerce.

South Korea, and Japan, reflecting their strong emphasis on basic research. During 2016–2020, China's spending on basic research grew at an annual average rate of 17%, and the share of basic research spending in Chinese R&D investment has trended upward.[16] Nevertheless, the share was only 6.03% in 2018. The insufficient spending on basic research results in a weak foundation for technological development and poor capabilities in radical innovations and inadequate foundations for technological development.

One critical reason for China's insufficient spending on basic research is the lack of corporates' significant investment in this area. In 2018, corporate R&D spending accounted for 76% of Chinese R&D spending, but basic research made up only 0.22% of corporate R&D spending. Consequently, the share of companies spending on basic research was only 3% in China, far below the average share of 28% in the US.

Chinese companies are reluctant to participate in basic research.[17] During the years when China was a planned economy, companies mainly focused on production, while universities and research institutes were in charge of technology research.[18] Consequently, it was long believed that basic research should be done by universities and research institutes instead of companies. Chinese firms are unwilling to participate in basic research as they believe they can acquire technologies through technological transfer.

Meanwhile, Chinese companies historically have not been actively involved in national science and technology programs. In particular, National Natural Science Foundation's projects and the "973 program" that both focus on fundamental science have been rarely undertaken by companies. China carried out its national key lab program as early as in 1984, while it did not create its corporate key lab scheme until 2006. Although China now emphasizes the role of companies in key national R&D projects, companies remain primarily focused on applied research and universities or research institutes are still in charge of basic research tasks.

In addition, Chinese demand for basic research is weak due to its position in the global industrial division. As the world's largest manufacturer of finished goods, China focuses on processing and assembly procedures in the global value chain. Low-tech manufacturing industries make up the largest proportion in its exports.[19] Consequently, domestic companies have tepid demand for R&D, especially for basic research. According to a survey by McKinsey in early 2021, R&D activities

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[16] Source: China Statistical Yearbook on Science and Technology.

[17] Sui, J., Lian, Y., Qu W. (2013). Corporate basic research and innovation breakthroughs. Studies in science of science 1, 141–148.

[18] In the Soviet Union, industrial sectors were mainly in charge of development and application research. In 1998, 87% of its science experts worked at universities and research institutes. Source: Chen, S., (1991). Basic research and development strategy in soviet union. Science & technology international 4, 23–28; Zhu, B., (1986). Status quo and reforms on science R&D system in the US, soviet union and japan. Studies in science of science 4, 67–68.

[19] For more details, please refer to Sect. 1.1 of this chapter.

targeting product cost reduction made up two-thirds of R&D spending by Chinese companies.[20]

Private companies have lower R&D intensity than state-owned enterprises (SOE). In particular, their spending on basic research is relatively low. In 2019, private companies accounted for 39.6% of total R&D spending from Chinese companies and 71% of domestic R&D spending on high-tech areas.[21] However, their R&D intensity and spending on basic research are both relatively low. In high-tech areas, SOEs had R&D intensity of 4.9%, while the R&D intensity of all Chinese companies was only 2.7%. We believe this suggests that SOEs focus more on basic research and that their R&D output is stronger than other firms.[22]

1.2.1.2 Large Talent Base, but Larger Room for Improvement

China has the largest talent base in the world. According to data from the Organization for Economic Cooperation and Development (OECD), China had a total of about 1.87mn researchers in 2018, more than 1.43mn in the US, 680,000 in Japan, 430,000 in Germany, and 340,000 in India.[23] Regarding higher education and professional knowledge, China leads the world in the number of science, technology, engineering, and mathematics (STEM) graduates with a bachelor's degree or above—China's 1.79mn graduates in 2018 represented three times that of the US, nine times that of Germany and the UK, 12 times that of Japan, and 13 times that of South Korea.

However, China still lags in terms of talent per capita. Data from the OECD and the World Bank showed that the number of researchers per 1,000 workers in China in 2018 was only one-sixth that of South Korea, one-fifth that of Singapore, and one-fourth that of the US, Germany, and Japan, and slightly lower than the level commensurate to GDP per capita. Compared with the US, major developed countries in Europe, Japan, and South Korea, China had a lower number of years of education completed per capita in 2018, which was also below the average level corresponding to its GDP per capita (Fig. 1.13).

Lack of high-quality talent is particularly prominent in China's key industries. According to data from Macropolo, 59% of the top artificial intelligence (AI) workers choose to work in the US, followed by China (11%), Europe (10%), Canada (6%), and the UK (4%). Tsinghua University and Peking University are the only two Chinese institutions that are included among the top 25 AI research institutions in

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[20] Source (in Chinese): https://mp.weixin.qq.com/s/gjLrvyFGCzVTYpbCT7j9og.

[21] Source: China Statistical Yearbook on High-tech Industries, and China Statistical Yearbook on Science and Technology.

[22] Ye, J., Lin, J., Zhang, P. (2019). The special role of chinese SOEs from the perspective of knowledge spillover. Economic research, 6, 40–54. Wang, F., Zhao L., and Dai X: The factors affecting heterogeneity of chinese firms' preferences for basic research. Science research management 42(3), 11–22.

[23] OECD defines researchers as professionals engaged in creation of new knowledge, product processes, methods and systems, and related project management.

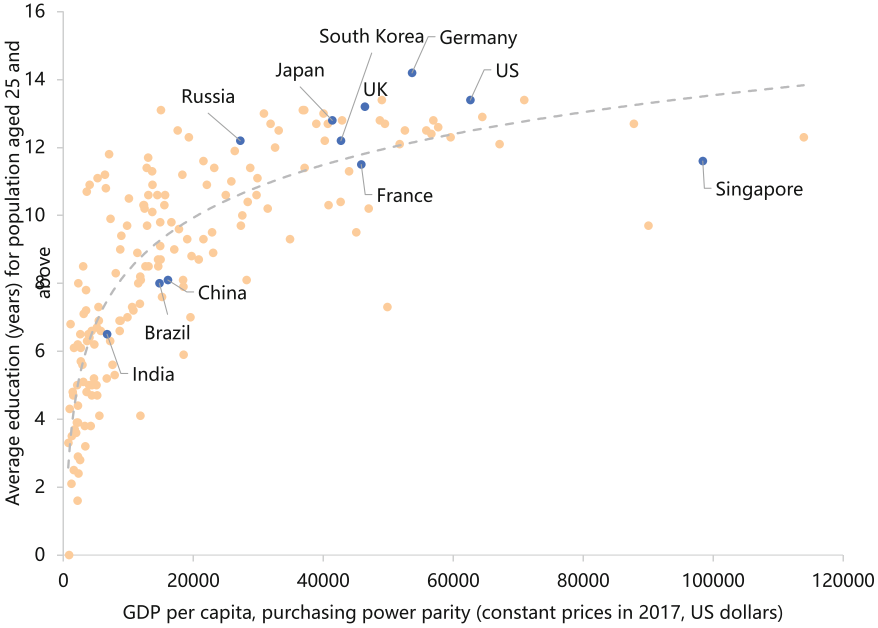

Fig. 1.13 Number of years of education completed. *Note* 2018 data. *Source* OECD, World Bank, CICC Research

the world, ranking No. 9 and No. 18, respectively.[24] In the integrated circuit (IC) industry in China, holders of masters and doctoral degrees account for only 18% and 1% of total employees. The White Paper on Talent in China's Integrated Circuit Industry (2019–2020) published by the Shenzhen Semiconductor Industry Association, predicted demand for talent in the industry would reach 720,000 around 2021. However, there were only 199,000 graduates of IC-related majors from domestic colleges and universities in 2018.

From our perspective, talent resources are unevenly distributed among industries in China. Judging from A-share listed companies, the three industries with the highest proportion of employees with a bachelor's degree or above are banking (84.1%), non-banking finance (82.4%), and diversified finance (65.8%). These three industries do not have high demand for R&D but have more graduates with higher education, which may represent a misallocation of resources, in our view. Many talented workers are more inclined to be engaged in the financial industry rather than in R&D. This is related to the fact that the finance industry has a higher salary level than other industries.

We believe three supply-side challenges constrain the advancement of high-quality basic education, resulting in inadequate innovative personnel: The uneven

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[24] https://macropolo.org/digital-projects/the-global-ai-talent-tracker/.

distribution of high-quality basic education in China directly reduces the quantity of human capital. The strong incentive system of exam-oriented education has resulted in excessive investment in exam-oriented skills. Research-oriented universities should play an important role in turning human capital into innovative personnel, but their development potential is constrained by educational administration factors.

First, the quality of basic education in developed regions of China is high, but the distribution of spending on basic education is uneven among regions. Education expenditure as a percentage of GDP is 4.6% in China, and basic education expenditure accounts for 70% of total education expenditures. Both indicators are mediocre compared with those in major industrialized countries. However, the education expenditure per ordinary primary school student in developed regions is generally higher than that in underdeveloped regions. Data from the China Educational Finance Statistical Yearbook shows that the highest education expenditures per ordinary primary school student were in Beijing (at Rmb39,000), Shenzhen (at Rmb37,000), and Shanghai (at Rmb34,000) in 2019, while Henan had the lowest expenditure at only Rmb7,953. The coefficient of variation in public education expenditure per ordinary primary school student in China's provinces is 0.4, higher than that in public education expenditure per K-12 student in the US (0.3).

The uneven distribution of basic education spending also exists within regions. In 2018, the education expenditure per student at local rural primary schools was Rmb11,827, 7% lower than ordinary primary schools at Rmb12,737. The linkage between housing and education could exacerbate inequality in education opportunities, in our opinion. In addition to basic residential functions, housing also corresponds with basic public services. Data from ke.com shows that in major cities with high housing prices, housing near key schools has large premiums. High housing prices have become a threshold for high-quality education resources, exacerbating the uneven distribution of education resources.

Second, strong incentives for exam-oriented education has led to excessive investment in exam-oriented skills. The exam-oriented selection mechanism is a strong incentive system that increases the motivation of students, parents, and teachers and enhances cognitive abilities of students. This is a crucial reason for Chinese students ranking among the best in the Programme for International Student Assessment (PISA) test. However, such a one-dimensional strong incentive system could easily lead to a "prisoner's dilemma" situation where students place too much effort into improving exam-oriented skills instead of increasing human capital, resulting in a waste of resources.

Third, research-oriented universities should be given more space for innovation, in our opinion. Research-oriented universities turn human capital into innovation, and high-quality research-oriented universities can greatly increase the proportion of innovators. Bloom et al. (2021) found that disruptive technology centers are more likely to appear in areas with universities and highly skilled labor.[25] China has a large number of universities but a relatively small number of high-quality research-oriented

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[25] Bloom, N., Hassan, T. A., Kalyani, A. (2021). The diffusion of disruptive technologies. National Bureau of Economic Research.

universities. In our view, one reason is that the development of research-oriented universities is influenced by administrative factors.

China's spending on higher education is relatively low, and government appropriation plays a significant role. Based on data from the China Educational Finance Statistical Yearbook, China's education spending accounted for about 4% of GDP in 2018, lower than the proportion in the US and the UK (about 6% each), according to the OECD. In addition, government appropriation accounted for 67% of China's spending on higher education, much higher than the proportion in the US (35%) and the UK (26%).

Government appropriation to higher education ensures equity in education, but it also imposes constraints on higher education institutions. Compared with the US, higher education in China is cheaper and more inclusive. However, colleges and universities in China also face more constraints when using government funding. For example, 82.5% of scientific and technological workers think researchers with certain administrative titles are more likely to obtain research funding.[26]

A well-structured talent system both expands the supply of talent from the domestic education system and attracts cutting-edge talent through its favorable environment around the world. In the US, immigrants account for 18% of all talent. Further, 58% of all global immigrant talent chooses the US (Fig. 1.14), and 42% of US PhD graduates in STEM majors in 2019 were students from other countries. Such immigrants are often the top scientific and technological workers trained by their home countries.

In comparison, China sees a large outflow of talent, especially in STEM majors. China has a large number of students abroad. In 2017, there were about 928,000 Chinese students abroad, accounting for about 17.5% of global students abroad. The proportion of Chinese students studying STEM majors in the US has increased, while the proportion of STEM graduates returning to China is relatively low. In the 2019–2020 academic year, there were about 181,000 Chinese students majoring in STEM in the US, accounting for nearly 50% of the total number of Chinese students studying in the US. This proportion has been increasing since 2012. According to the Annual Report on the Development of Chinese Students Studying Abroad (2020), students majoring in economics and management accounted for about 46% of returning graduates, while students majoring in science and engineering accounted for 31%.

China's attractiveness to top talent needs to be improved. Among students earning doctoral degrees in the US, Chinese students take up a much larger proportion than students from other countries. Data from the US National Science Foundation showed about 6,300 Chinese students received doctoral degrees in the US in 2019, three times the number of Indian students, 13 times the number of South Korean students, and 26 times the number of Japanese students. Also, 80% of Chinese students who have earned a doctoral degree in the US are willing to stay there, much higher than the proportion of 51% for Japanese students and 65% for South Korean students. Data from Macropolo shows only 31% of the top AI researchers working in the US are from the US, and the remaining 69% are international students who stay in the US

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[26] According to a survey on scientific and technology by the Development Research Center of the China Association for Science and Technology.

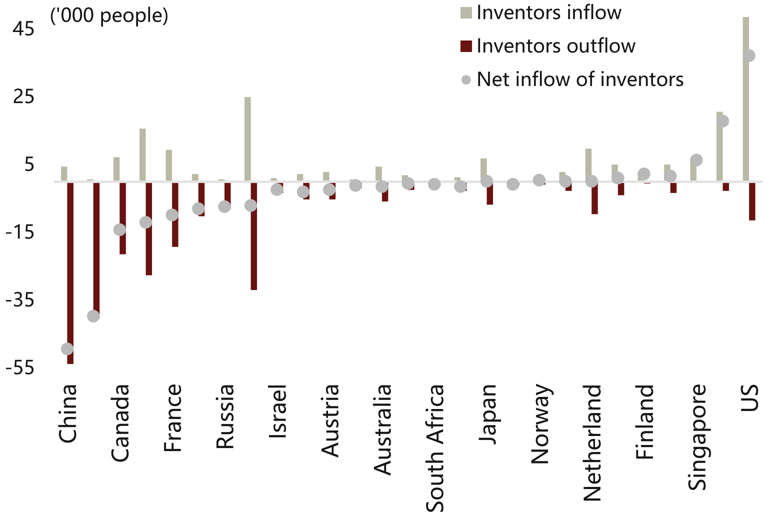

Fig. 1.14 Number of immigrant talent and emigrants of select countries, 2001–2010. *Source* Fink, C, E Miguélez, and J Raffo (2013), "The global race for inventors", WIPO Economic Research Working Paper, CICC Research

after graduation. China accounts for the highest proportion of such students (27%), with all of Europe accounting for 11%. In 2020, 88% of Chinese PhD students in the US focusing on AI chose to work in the US after graduation, while 10% chose to return to China.[27]

Excessive competition may increase the difficulty of attracting talent. The talent market is first of all a labor market, with relatively fixed supply. For such a market, using subsidies and other means to stimulate demand may lead to an increase in wages rather than an increase in talent.[28] Market entities may make excessive commitments in order to attract talent amid competition. Such a phenomenon would intensify the information asymmetry in the labor market, weaken the role of the signaling mechanism in the labor market, reduce the efficiency of matching between talent and employers, and even lead to adverse selection in the talent market.[29] This may reduce the number of workers a college or university attracts in the end due to market friction. For example, some colleges and universities may over-promise research funding, salary, benefits, and pace of career advancement when attracting talent, and fail to deliver on their promises. This weakens the efforts to attract talent and increases the difficulty of attracting talent in the future.

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[27] Macropolo The Global AI Talent Tracker.

[28] Romer, P. M. (2000). Should the government subsidize supply or demand in the market for scientists and engineers? Innovation policy and the economy, 1, 221–252.

[29] Greenwald, B. C. (2018). Adverse selection in the labor market. Routledge.

1.2.2 Technological Innovation Output: Five Patterns of China's Progress in Playing Catch-Up in Knowledge Innovation Over Three Decades

Technological innovation output converted from R&D and talent inputs could most directly reflect a country's scientific research strength in the past. It can be regarded as the "transcript" of the country's achievements in technological innovation. Moreover, achievements in technological innovation could also guide a country's technological innovation input and construction of an innovation system. By comparing the achievements of technological innovation activity in various countries, we could gain insights and draw lessons from technological innovation activity in the past, which gives direction to the improvement in innovation system and resource allocation. Therefore, a review of previous achievements in technological innovation in a results-oriented approach provides guidance for improving China's technological innovation activity.

Human society's technological innovation activity can be divided into two types: Knowledge innovation and production innovation. In a nutshell, knowledge innovation refers to human activity involved in developing basic science through scientific research and applying new scientific knowledge. By contrast, production innovation refers to the combination of knowledge production and production of goods and services with the help of innovative thinking. Compared with production innovation, knowledge innovation not only is a prerequisite for humanity to understand and change the world, but also determines the breadth and depth of production innovation. In addition, while production innovation tends to directly affect production in the near term, knowledge innovation exerts a greater impact on production activity in the future. Therefore, in this section, we place our focus on knowledge innovation in China's technological innovation activity. Production innovation will be examined in detail in the following chapters.

Among the achievements that can be studied, academic publications and invention patent applications are recognized by international institutions[30] as key indicators of achievements in knowledge innovation in various countries due to their good comparability, objectivity, and high relevance to science and technology. In order to present China's achievements in knowledge innovation since the 1990s in a comprehensive way, we refer to the Microsoft Academic Database (MAD), Nature Index, SCImago Journal & Country Rank, and other databases that cover about 300mn academic papers published in nearly 50,000 journals in 27 disciplines, e.g., mathematics, physics, chemistry, life sciences, environmental sciences, materials science, and medicine. We also use databases from the World Intellectual Property Organization (WIPO) and relevant national patent offices to analyze more than 3mn PCT patent applications[31] in electrical engineering, mechanical engineering, chemistry,

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[30] Such as OECD, EuroStat, WIPO, among others.

[31] PCT refers to Patent Cooperation Treaty, through which inventors can seek patent protection in other PCT contracting states for their inventions.

instruments, and other fields, which can be further divided into 35 technology fields under the above five sectors.

We summarize the evolution of China's technological innovation output in the past three decades and highlight five patterns of China's knowledge innovation. We hope that the five patterns can help us better understand the pros and cons of China's scientific and technological innovation activity in the past, and provide clues for improving China's technological innovation ecosystem in the future.

1.2.2.1 Pattern 1: Catching Up in Quantity, and Narrowing Gap with Developed World in Quality

China was in the past a latecomer but is now taking the lead in academic publications, especially in STEM. The number of academic articles published from China each year accounted for less than 3% of the global total by 1995, far behind the 30% of the US. However, after nearly 30 years of catch-up, China saw its annual academic article publication output surpass that of the US to become the world's largest contributor of academic articles, accounting for about 16% of the world's total in 2020. Looking ahead, we believe that China may further enhance its advantage against the US in terms of annual academic article publication output.

Among all subjects, materials science, chemistry, and medicine were ranked the top three in China regarding the number of publications. Compared with the beginning of the 21st century, China's research article publications were increasingly concentrated on STEM fields over 2015–2020. The share of publication output of almost all STEM subjects in total publications over 2015–2020 was higher than that over 2000–2005.

The number of international patent applications that China filed through the Patent Cooperation Treaty (i.e., PCT patents)[32] in the 1990s was also very small. However, from 2000 to 2019, the average annual growth rate of the number of PCT patent

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[32] Since our purpose is to analyze China's technological innovation capabilities in various industries in this chapter, we focus on international patent applications, i.e., patent applicants seeking patent protection for their inventions in multiple countries. Such inventions often have greater commercial potential and stronger technological competitiveness. In practice, the collection of patent applications filed by applicants in different countries (or regions) in order to protect the same invention is called a "patent family". The concept of patent family in the following sections can be understood as invention.

Since filing patent applications through PCT has become the main method for Chinese inventors to apply for international patents, our analysis will focus on this type of international patent (family) in this chapter (referred to as PCT patent). According to data on international utility model patenting disclosed by the WIPO Statistics Data Center (updated in January 2021), utility model accounted for less than 1% of China's PCT patent applications. That means that more than 99% of PCT applications are applications for invention patents. Therefore, we regard PCT patents as invention patents in our following analysis. Because the US patent system does not include utility model, all the US patents mentioned in the following sections refer to invention patents.

applications filed by China was close to 26%,[33] versus 2%[34] in the US during the same period. This drove China to surpass the US to become the top filer of PCT patent applications in 2019. With the growing number of PCT patent applications filed by China, China's share of the world's total number of PCT patent applications has also trended upward year by year. From 2000 to 2020, China's share of the world's annual PCT patent applications expanded to 25% from less than 1%, while that of the US dropped to 21% from 41%. Specifically, the increase in the number of China's patent applications has mainly been driven by the electrical engineering sector. So far, patents in the electrical engineering account for about half of China's total PCT patent applications.

Some people believe that the rapid increase in the number of China's academic publications and PCT patent applications is driven by quantity-oriented policy incentives,[35] and that such policies may negatively affect the quality of China's knowledge innovation. However, multiple indicators show that China has also made significant progress in the past 20 years in terms of the overall quality of knowledge innovation, and that the "quality gap" between China and developed countries has been narrowing.

A higher number of citations indicates a greater level of recognition a paper receives from peers. Therefore, the number of citations is often regarded as an important indicator of the quality of an academic article. Compared with the number of citations in different disciplines in the US during the same period, we have found that the average number of citations for articles from China increased notably in the past 20 years. Among the articles published over 2000–2002 (by time of publication), the average number of citations for most China's articles was significantly lower than that of US ones.[36] Compared to the citation count ratio over 2000–2002, amid the increase in the total number of publications, the average number of citations for articles published in China compared to articles published in the US in various disciplines also increased over 2017–2019. That said, based on rankings of all subjects in terms of citation rate, although China still lags behind the US in STEM fields (Fig. 1.15), China has made progress in research quality over the past 20 years. In addition, from the perspective of patent, we have also found an increase in the number of China's PCT patent citations, which shows that the quality of knowledge innovation in China has been improving, and that the gap between China and the US has been narrowing.

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[33] Number of PCT applications in each country based on data disclosed by WIPO Statistics Data Center (updated in July 2021).

[34] According to our analysis based on data released by WIPO Statistics Data Center (updated in July 2021); patents' country information based on origin of the inventors.

[35] Cheryl, X. L., Jun, W. (2019). China's patent promotion policies and its quality implications, Science and Public Policy.

[36] The average number of citations for papers from China in nursing and dentistry fields was higher than that for US papers. The main reason was that the total number of publications in related disciplines was relatively small at the time. Except for several high-quality papers, including papers co-authored by Chinese academics and foreigners, it was difficult for other papers to get published, resulting in relatively high citations of related publications.

1.2.2.2 Pattern 2: China Still Accounts for a Small Share of Global Core Knowledge Network; Originality Remains a Weakness

Although the output of human knowledge can be random to a certain extent, it is rarely produced in isolation. The information on citing and cited publications lays a foundation for the establishment of a global knowledge network. Through such a knowledge network, we can gain an overall view of the "inheritance system" of human knowledge, and understand the importance of each innovation activity. This is of great significance for understanding the time, place, and technical field of innovation activity, as well as for exploring the evolutionary patterns behind such activity.

We extract information on research articles published and cited since 1995 from Microsoft Academic Graph as well as all PCT patent information since 1978 from

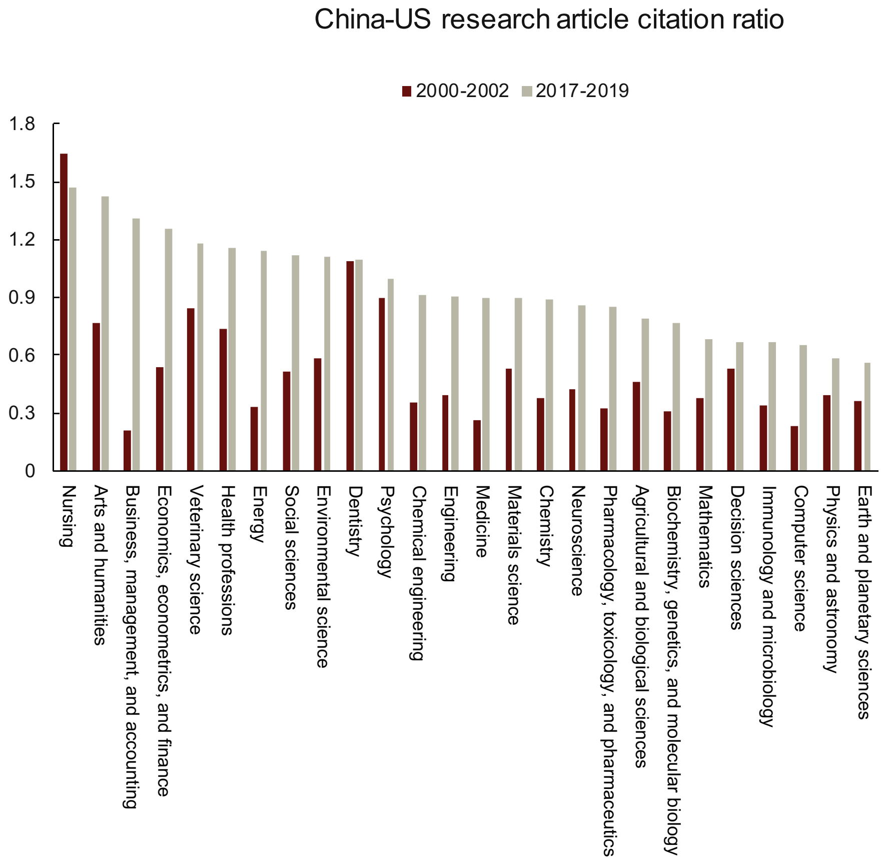

Fig. 1.15 The average number of citations of research articles in most disciplines in China increased significantly versus US counterparts. *Source* SCImago Journal & Country Rank, CICC Global Institute

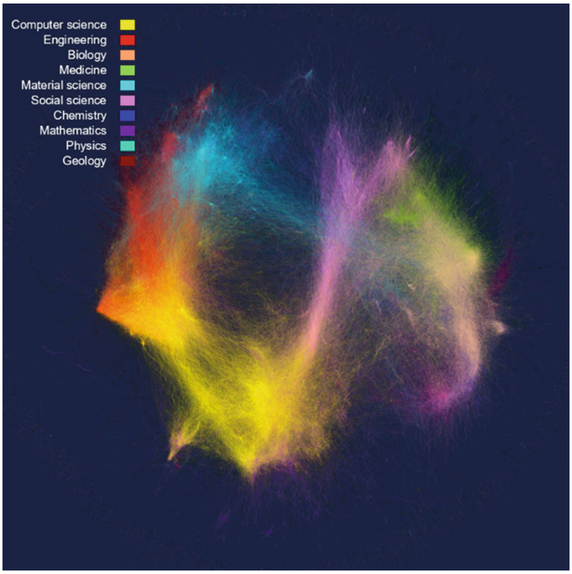

Fig. 1.16 Paper citation networks (1995–2020). *Note* The figure shows the mutual citation relationships of nearly 1.1 mn academic documents. The data includes research articles published from 1995 onward with complete country and discipline information. *Source* Microsoft Academic Graph, CICC Global Institute

EPO Patstat, and present their citation networks. In these citation graphs, each point (node) represents a paper or a patent, and the distance between points depends on the citation relationship between them. The closer the two points are in the network, the tighter their citation relationship is.[37] Areas with higher density in the network represent core fields of research, while areas with low density correspond to general knowledge or technologies applied in various disciplines or industries.

Figure 1.16 shows the citation networks of academic literature published since 1995. Some highly interrelated papers such as papers in computer science, biology, etc., have developed into relatively independent areas. In particular, in the computer science citation network (in yellow), most of the literature keeps expanding within its own knowledge system, and some mathematics and social sciences literature are derived on the right side of the computer science field. Engineering (in red) demonstrates a different scenario. Although it ranks No. 2 among all fields in terms of number of papers, its citation network intersects with a number of other disciplines, including computer science, materials science, and mathematics. This shows that backed by a large amount of academic literature in other fields, engineering continues to achieve innovative research output while offering support to innovative research in other disciplines. There are also some disciplines that are closely related to each other. They form an interwoven citation network around the basic disciplines. For example, materials science is relatively closely related to chemistry, medicine, and biology.

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[37] The citation relationships here include direct reference relationships and indirect, multi-level reference relationships.

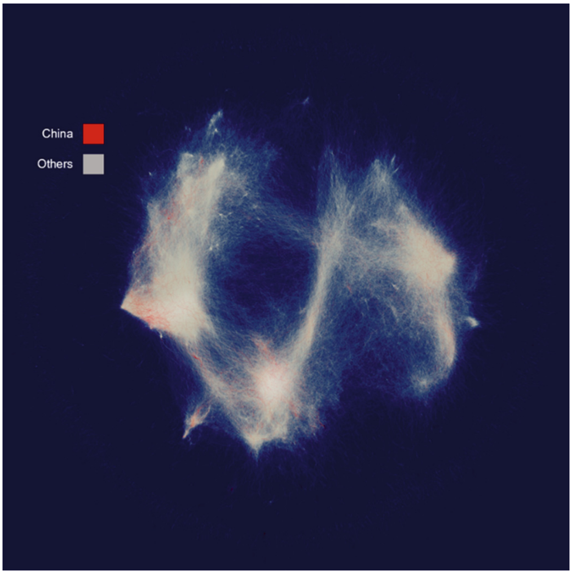

Fig. 1.17 Distribution of China’s academic papers (1995–2020). *Note* 1) This figure shows the mutual citation relationships of nearly 1.1 mn academic documents. The data includes research articles published from 1995 onward with complete country and discipline information. 2) Red dots represent papers from China and gray dots represent those of other countries. *Source* Microsoft Academic Graph, CICC Global Institute

As shown in Fig. 1.17, from the perspective of discipline structure, the citation networks of papers from China have mainly been distributed in the fields of computer science, materials science, and biology in recent years, while in other fields, there are only sporadic connections. In the citation network, papers closer to the core position of the citation cloud of a field are more frequently cited. However, most of the citation networks related to China in the figure are located at the edge of the corresponding discipline areas, and the density is low. This to a certain extent indicates that the proportion of papers from China in the core positions remains relatively low. In addition, in the citation network, we also note that currently, China’s academic literature tends to concentrate in applied science disciplines, while literature in basic science disciplines is insufficient.

Figure 1.18 shows the global citation network of PCT patents since 1978. Patents in the electrical engineering and chemistry sectors are relatively concentrated in terms of distribution, and they have little overlap with other sectors, indicating that there are more citations between these two sectors. In comparison, the mechanical engineering and instruments sectors are at the core of the citation network. They are intertwined with each other and have more connections with other sectors. This suggests that the mechanical engineering and instruments sectors play a role in providing extensive general technology and product support for other sectors.

Figure 1.19 depicts the positions of China’s PCT patent applications in the global patent citation network. We can clearly see that China’s PCT patents are mainly concentrated in the peripheral area of the electrical engineering field, with darker colors only in some areas. The distribution of China’s patents is more sporadic in other fields. This is largely in line with our previous discussion on academic publications.

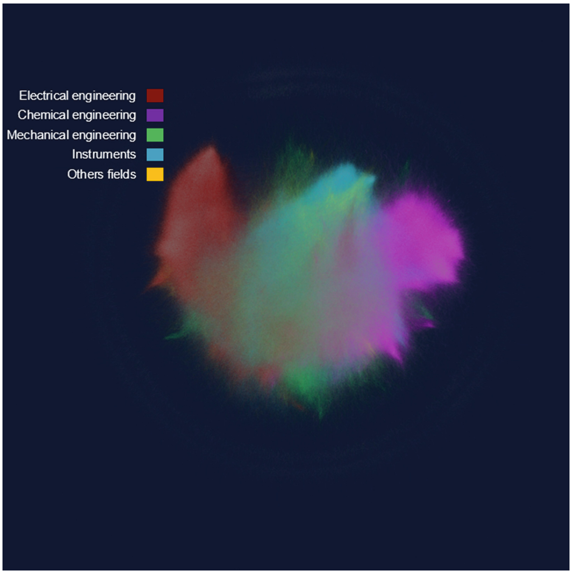

Fig. 1.18 PCT patent citation network for the technology sector (1978–2020). *Note* The above figure shows the mutual citation relationships of nearly 2.97 mn PCT patent families. The data includes all PCT patent families filed from 1978 onward, and these patent families were cited by another PCT patent family at least once. *Source* EPO Patstat, CICC Global Institute

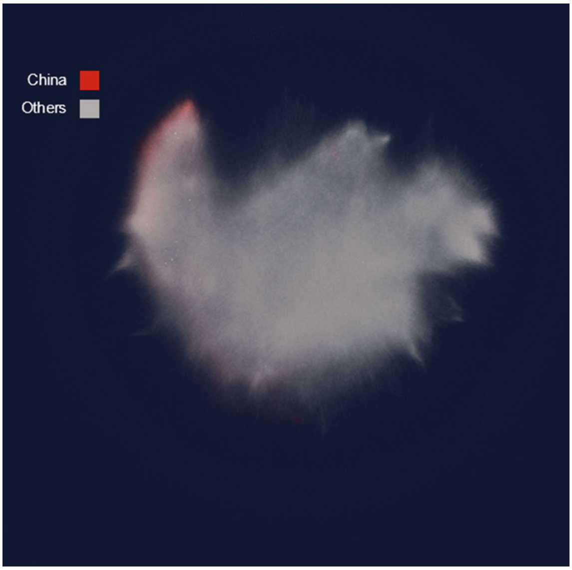

Fig. 1.19 Distribution of China's PCT patent applications (1978–2020). *Note* 1) The above figure shows the mutual citation relationships of nearly 2.97 mn PCT patent families. The data includes all PCT patent families filed from 1978 onward, and these patent families were cited by another PCT patent family at least once; 2) The red dots in the above figure represent China's patents, and the gray dots represent those of other countries. *Source* EPO Patstat, CICC Global Institute

Originality has self-evident importance for science, but objectively measuring originality poses a formidable challenge. We introduce a new indicator to measure the originality of a work in knowledge innovation.[38] Specifically, if the citation relationship between the subsequent work citing an achievement in knowledge innovation

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[38] Shibayama, S., Wang, J. (2020). Measuring originality in science, Scientometrics.

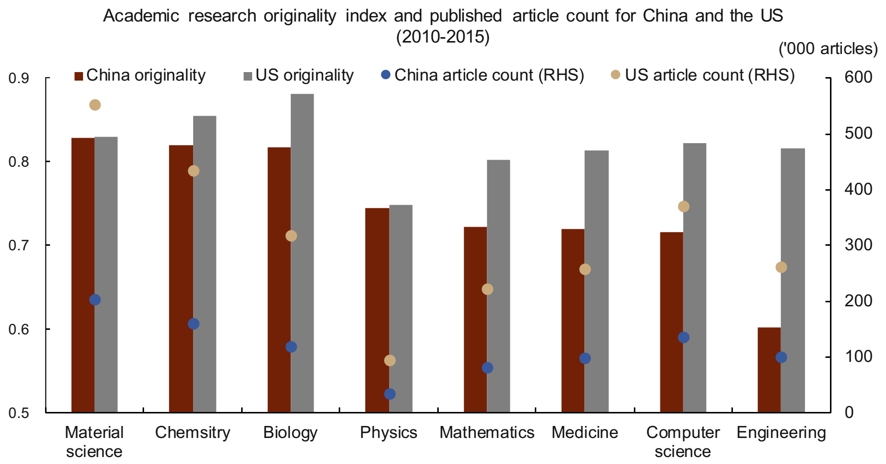

Fig. 1.20 China lags the US in terms of originality in most STEM disciplines. *Source* Microsoft Academic, CICC Global Institute

and its reference is not close, the originality index of the achievement is relatively high. Compared with the traditional method of using citation count to measure its quality, the originality index also takes into account the previous citation relationships, and could thus reflect the uniqueness, innovativeness, and importance of the achievements in a more objective and comprehensive way.

We use data from Microsoft Academic to calculate the originality index of China's and US academic papers from 2010 to 2015. We have found that the level of originality of papers from China is similar to that of US papers in materials science and physics, but lags behind the US in most other disciplines, especially in medicine, computer science, and engineering (Fig. 1.20).

In terms of the originality indexes of PCT patents (2015–2017 filing years), the US outperformed China in almost all fields. Among the five main technology sectors, the originality of China's patents in the electrical engineering discipline was relatively high. It is noteworthy that the level of originality of China's patents was slightly higher than that of their US counterparts in the semiconductor field. One possible reason is that due to limited technological and research collaboration, China had to carry out independent R&D in the semiconductor field, which to a certain extent increased the originality of China's patents in this field.

1.2.2.3 Pattern 3: "Strong Industry, Weak Academia" in Conversion of Knowledge Innovation, Scarcity of Frontier Tech Companies in the Market

The conversion of achievements in knowledge innovation can take two forms: The conversion of basic research innovations into commercial patents, which could be

Conversion efficiency of basic research results	Agriculture	Material	Energy	Internet information	Manufacturing and engineering
China	1.2%	1.9%	1.7%	0.1%	0.0%
US	6.5%	17.8%	19.5%	30.0%	39.3%
Japan	4.0%	1.1%	3.4%	0.2%	1.8%

Fig. 1.21 China lags behind the US and Japan in conversion efficiency of basic research (2020). *Source* Evaluation of transformation efficiency of basic research results in China's key technical fields,[41] CICC Global Institute

measured via the conversion efficiency of basic research results[39]; and the adoption of patented technology in the industry, which could be measured via the rate of patent commercialization.[40]

In China, basic research work is mainly undertaken by universities and research institutes. From the perspective of conversion of basic research results into commercial patents, China is still a laggard compared to the US and Japan. In the internet information sector and the manufacturing and engineering sector, basic research provides little support for related commercial patents in China (Fig. 1.21), indicating that the connection between basic research and the development of commercial technologies is weak.

The overall commercialization rate of China's patents is not low. However, it lags well behind developed countries in the commercialization of commercial patents from universities and research institutes. Similar to enterprises in many developed countries, Chinese enterprises also play a dominant position in patent application. The number of PCT patent applications submitted by Chinese enterprises accounted for more than 80% of China's total patent applications in 2018. The patent commercialization rate of Chinese enterprises is about 45%, close to the rates in developed countries, and it raises the overall commercialization level of Chinese patents. However, the commercialization rate of patents from Chinese universities and research institutes was 3.8% in 2018, significantly lower than that in the US (50.4%),[42] which could be a drag on the average commercialization rate.

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[39] Conversion efficiency of basic research results: The proportion of basic research results that obtain high-quality patents in a certain field/the proportion of high-quality patents contributed by basic research in this field.

[40] According to the State Intellectual Property Office of China, the rate of patent commercialization refers to the ratio of the number of patents used by patentees to produce products that are launched in the market to the number of active patents they own. For example, if a company has 100 active patents, 30 of which are used to produce products that have been launched in the market, then the rate of patent commercialization is 30%.

[41] Wu, F., Li, Y., Miao, H., Huang, L. (2021). Evaluation of the transformation efficiency of basic research results in China's key technical fields, Scientific Research.

[42] Wu, F., Li, Y., Miao, H., Huang, L. (2021). Evaluation of the transformation efficiency of basic research results in China's key technical fields, Scientific Research.

Scarcity of frontier tech companies might be an impediment to application of knowledge innovation achievements. China accounts for relatively high proportions of global academic publications and patent applications for all 11 frontier technologies[43] defined by the United Nations Conference Trade and Development (UNCTAD). For example, as of 2018, China's academic papers in the 11 frontier fields such as artificial intelligence (AI), Internet of Things (IoT), big data, and blockchain accounted for 13% of the global total, versus the 21% in the US; China's patents accounted for 22% of the world's total, versus the 30% in the US, indicating that China performed relatively well overall.

However, world-leading enterprises in frontier technology areas are scarce in China, with drones and solar photovoltaics (PV) being the only exceptions. This may have something to do with the fact that knowledge innovation in frontier fields has not yet helped relevant enterprises enhance their competitiveness in China. Another explanation is that relevant Chinese enterprises may not yet possess enough competency in cutting-edge fields, which hinders the conversion of achievements in knowledge innovation. In either case, it shows that China faces constraints in the application of knowledge innovation in frontier fields.

1.2.2.4 Pattern 4: Behind High-Quality Innovation is Comparative Advantage, Which is Both a Driving Force and a Constraint

Measured by achievements in research, China stands out in some areas, while it slightly underperforms in others. In areas featuring a large quantity of high-quality research and high conversion or commercialization rates, market forces are usually at play. In particular, the areas in which China performs well in knowledge innovation activity are often areas in which China shows comparative advantages in international trade.

As we mentioned earlier in this chapter, China's knowledge innovation in the electrical engineering industry shines in terms of both quality and quantity. Meanwhile, international trade activity in China's electrical engineering-related industries is also strong. To explain this correspondence, we have found that the "hidden comparative advantage" plays an important role. According to the OECD's classification for manufacturing industries (2016),[44] technology products can be divided into four categories, namely high, medium-high, medium, and medium-low technology products. High-tech manufacturing mainly includes aircraft, spacecraft, and related machinery; computer, electronic, and optical products; as well as pharmaceuticals. China has not yet fundamentally changed the fact that its comparative advantage mainly lies in labor-intensive sectors. Therefore, high-tech manufacturing does not seem to be in line with the country's comparative advantages. However, if we categorize the medium-high-technology industries defined by the OECD based on their

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[43] UNCTAD, Technology and innovation Report 2021.

[44] Galindo-Rueda, F., Verger, F. (2016). OECD taxonomy of economic activities based on R&D intensity.

capital intensity and technology intensity, we would find that computer and communications shows the most substantial comparative advantage among the high-tech industries in China.

With reference to the OECD's definition, we draw a scatter plot of the six medium-high technological manufacturing industries in China and the US based on the intensity of capital and technology (Fig. 1.22). In contrast to the general perception of high-tech industries, in the US, the capital intensity of computers, communications, and other electronic equipment industries is lower than that of the aerospace and pharmaceutical industries. Moreover, the capital intensity of the computer and communications industry is even lower than that of some medium-high technology industries such as the automobile and chemical raw materials and products industries. The computer and communications industry is relatively labor-intensive among high-tech industries, which perfectly fits the comparative advantage of China in terms of labor endowment. Therefore, China has formed a virtuous circle between knowledge innovation and corporate profits in computer, communications, and electronic equipment.[45]

In fact, the positive feedback relationship between comparative advantages and innovation capabilities in China's electrical engineering field is not an isolated case. Following the OECD's classification standard of manufacturing industries (2016), we calculate the revealed comparative advantage (RCA) index in terms of patents and exports of China and the US under the four technology categories in 2000 and 2019, and have found the RCA of patents and the RCA of international trade in corresponding fields basically maintained a clear positive correlation. For example, the comparative advantage of the US in international trade lies in the high-tech field, which remains unchanged over the past two decades. Correspondingly, the comparative advantage of its patent applications is also notable in the high-tech field. The sectors in which China had comparative advantages in 2000 were mainly medium-low-tech, labor-intensive industries. Correspondingly, the comparative advantages of China's patent applications around 2000 were also concentrated in medium-low tech areas. However, in 2019, China's comparative advantage shifted to the high-tech field, mainly to the computer and communications industry, and we note that there was a similar shift in the RCA index of patent applications.

Given the strong correlation between knowledge innovation and the comparative advantage in trade, we believe market opportunities can guide China's knowledge innovation activity. However, it also imposes constraints on the leapfrog development of China's knowledge innovation. At present, China does not have comparative advantages in a number of fields, such as aerospace and pharmaceuticals, but these fields are of great significance to China's development. It is difficult to incentivize knowledge innovation activity in these fields relying solely on market forces. Therefore, how to overcome restrictions from comparative advantages and let the government play its role has become a crucial issue that needs to be addressed in China.

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[45] According to the WIPO PCT Yearly Report 2019, China's PCT applications in the electrical engineering industry mainly came from tech giants such as Huawei, ZTE, BOE, OPPO, and Tencent. Over 2016–2018, these companies ranked No. 1, No. 5, No. 7, No. 17, and No. 28 in terms of the number of PCT patent applications among company applicants. In 2018, among the published PCT patent applications filed by Huawei and ZTE, 95% are in the electrical engineering industry, and the ratio reached 64% for BOE.

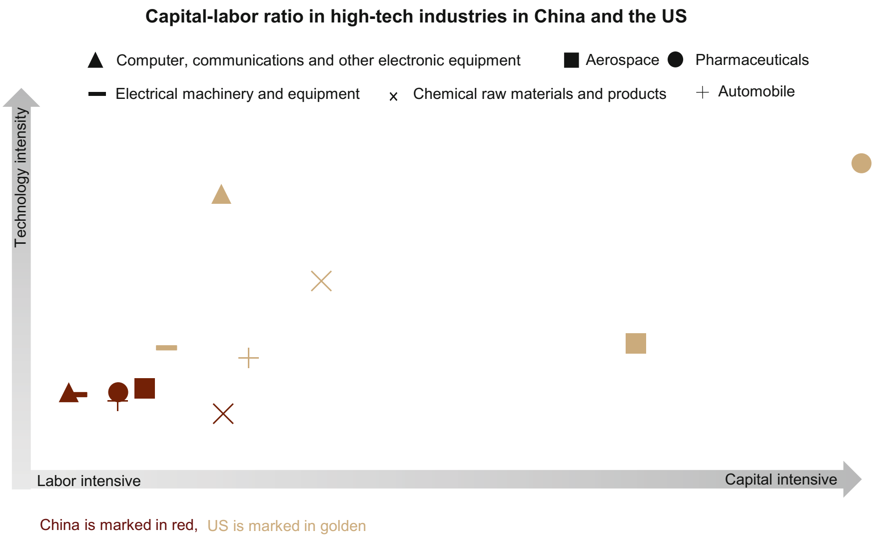

Fig. 1.22 China shows comparative advantages in computer and communications fields. *Note* 1) Capital labor ratio refers to net value of fixed assets of the industry/number of employees (Rmb10,000/person, based on data released by Shanghai Academy of Social Sciences), and technology intensity refers to the proportion of researchers in the industry; 2) US indicators in gold use 2016 data. Chinese indicators in red use 2017 data. *Source* NBSC, US National Science Foundation, US Bureau of Economic Analysis (BEA), CICC Global Institute

1.2.2.5 Pattern 5: Growth in International Collaboration in Knowledge Innovation Has Slowed in China

Cooperation between scientific researchers from different countries can facilitate the generation of new ideas. It can not only improve efficiency in problem solving, but also provides an important way for sharing the achievements of knowledge innovation. In practice, international cooperation can help researchers cut research expenses, share research resources, and investigate global academic topics.[46] Thus, it has become an important way to improve the efficiency of scientific research. For example, in 2016, China-US co-authored STEM papers accounted for 23% of all internationally co-authored papers in STEM disciplines in the US and 46% of all internationally co-authored papers in STEM disciplines in China,[47] indicating that China and the US were key partners for each other in academic collaboration in STEM disciplines, and that China has become an important participant in international academic cooperation.

However, the growth of China's participation in international academic cooperation has slowed in recent years. Since 1995, major developed countries have

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[46] National Science Board, Science & Engineering Indicators 2018.

[47] National Science Board, Science & Engineering Indicators 2018.

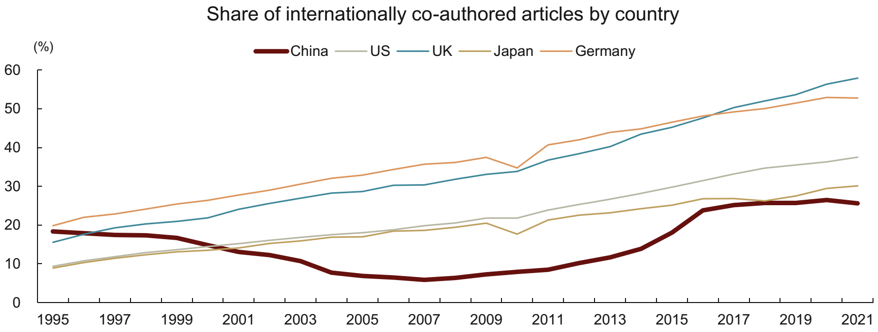

Fig. 1.23 China's proportion of internationally co-authored papers grew after 2006 and flattened recently. *Source* Microsoft Academic, lens.org, CICC Global Institute

strengthened international academic collaboration, with the proportion of internationally co-authored papers on the rise. In contrast, China's international academic cooperation could be divided into several stages (Fig. 1.23). From 1995 to about 2007, the growth in output of domestic papers outpaced that of internationally co-authored papers, resulting in a decline in the proportion of internationally co-authored papers. From 2007 to 2016, China started to accelerate its integration into the global academic system and ramp up international collaborative research, pushing a rapid increase in the proportion of collaborative papers. Since 2016, the proportion of international collaborative papers in China has still been lower than that in developed countries, and the upward trend has shown signs of stagnation or even decline, while the proportion of collaborative papers has continued to rise in developed countries.

The number of internationally co-invented PCT patents in China has stagnated since 2013 between 3,000 and 5,000 per year. It has not risen proportionally to the increase in the overall number of PCT patent applications in China, and the share of international co-inventorship has decreased significantly.[48] The decline in the proportion of patent applications jointly filed by Chinese and foreign inventors reflects the improvement in China's independent technological innovation capability. However, it could also exert an adverse impact on the transformation of China's industrial structure. Since 2013, China has started to push the transformation of its industrial structure by changing its extensive growth model and boosting domestic demand. However, China is positioned toward the lower end of the global value chain with limited need for innovation, while developed countries often demonstrate advantages in innovation on the upstream end of the global value chain. Domestic

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[48] The decline in the China's share of international co-inventorship in 2001 was attributable to the notable increases in China's non-collaborative PCT patent applications that year, which largely resulted from China's accession to WTO in 2001 and the implementation of the Patent Law (2000 Amendment). Over 2000–2018, the average annual growth rate of the number of China's internationally co-invented PCT patents was 17%, and that of the total number of China's PCT applications was 25% (China's international co-inventorship refers to collaboration between Chinese mainland applicants and non-Chinese mainland ones. Data from EPO Patstat).

companies usually establish cooperative relationships with foreign partners before a country starts its industrial upgrading. However, when the country begins to move up along the global value chain, its competition with developed countries may intensify, resulting in less willingness to cooperate. Overall, the stagnation of patent cooperation between China and foreign countries indicates a major loss in social efficiency and requires policy intervention, in our view.

1.3 Innovation Economics in Application for Improving Value Chain Security

As we mentioned in Pattern 5 of the previous section, China is usually positioned at the relatively low end of the global value chain, which is consistent with our analysis in the first section, that China faces risks of decentralization. However, analysis of risks from the perspectives of exports and imports only helps identify whether there are horizontal or vertical risks in each industry, and does not inform us on how to improve industry chain security. As discussed in Sect. 1.1, from the perspective of international competition, the key to improving a country's industry chain security is to increase the country's irreplaceability in the industry chain. How is irreplaceability measured? Generally speaking, a segment that is more irreplaceable should have stronger pricing power. Among micro-level financial indicators, we believe gross margin can better measure pricing power than ROE. This is because ROE depends not only on the irreplaceability of the company itself, but also on the asset turnover ratio influenced by the business cycle, the net margin influenced by the accounting system, and the leverage ratio that represents the capital structure. Relatively speaking, gross margin can better reflect the company's own pricing power.

Hereinafter, we will use gross margin as a measure of irreplaceability and R&D intensity as a measure of innovation capability to depict the industry chain and R&D chain in an attempt to discuss how to improve industry chain security. It should be noted that not all industries with disadvantages or risks require high policy attention. For example, China's share of global imports is 22% for cosmetics and 6% for pharmaceuticals, and the import source CR4 is 78% for cosmetics and 54% for pharmaceuticals. However, this does not mean that from a policy perspective, more attention should be paid to cosmetics than to pharmaceuticals. Considering the different social significance of each industry, policy makers should concentrate resources on improving industry chain security in key areas.

Based on the above analysis of advantages and disadvantages of various industries, and taking into account the criteria of "systemic importance" and "promising development prospects," we identify three key areas of industry chain security, namely digital technologies, green industries, and biotechnologies. We believe the digital economy is the most "systemically important" field of China's economy in the next

10 years, and that industrial digitization will bring profound changes to many industries.[49] The green economy should bring both new constraints and new opportunities to China's economy in the next 40 years under the goal of carbon neutrality,[50] and we see enormous development prospects for new technologies and industries such as hydrogen energy, carbon capture, and energy storage. The COVID-19 pandemic has highlighted the systemic importance of the bioeconomy. Against the background of global warming, the bioeconomy may become increasingly important for the sustainable development of human society, whether in terms of food production or disease prevention and treatment. The great success of artificial intelligence (AI) in predicting protein structures also means that the development of the digital economy may accelerate the development of the bioeconomy.

1.3.1 Implications from Three Major Areas: Industry Chain and R&D Chain Are Highly Positively Correlated

1.3.1.1 Digital Economy: The US Occupies High-Margin Segments of the Industry Chain Through High R&D Investment

Our analysis of the industry chain and R&D chain shows that China's software industry needs to improve its security. In the software industry, infrastructure software has the highest gross margin and the highest level of irreplaceability. The US is far ahead of other economies in terms of gross margin and revenue of infrastructure software, supported by its much higher R&D investment in this segment. The gross margin of application software is between the gross margins of infrastructure software and IT services. The US also leads in gross margin and revenue of application software, backed by its much higher R&D investment than other economies (Fig. 1.24). IT services has the lowest gross margin and the lowest level of irreplaceability. Although the US has higher revenue in IT services than other economies, it does not have much higher gross margin and R&D intensity in this segment.

1.3.1.2 Green Economy: R&D Investment Supports China's Current Leading Position

The green economy is an emerging field in which China currently holds international competitive advantages, and solar and electric vehicle (EV) batteries are two industries in which China has more prominent advantages. In 2019, in the photosensitive semiconductor industry, China accounted for 21% of global exports, much higher than its 7% share of global imports. In the storage battery industry, China accounted for 28% of global exports, more than three times its 8% share of global imports; and

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[49] See our series of reports on the digital economy published in September 2020.

[50] See our series of reports on carbon neutrality published in March 2021.

its share of global lithium-ion battery (LIB) exports was 38%. An important reason for China's advantages is that the country has maintained a high R&D expense ratio in major segments of the industry, which has enabled Chinese companies to take large market shares and enjoy high gross margins. In the solar industry chain, the midstream and upstream manufacturing segments are dominated by Chinese companies, and the US and Germany only maintain some competitiveness in the inverter segment. It is worth noting that the advantages of the US and Germany in the inverter

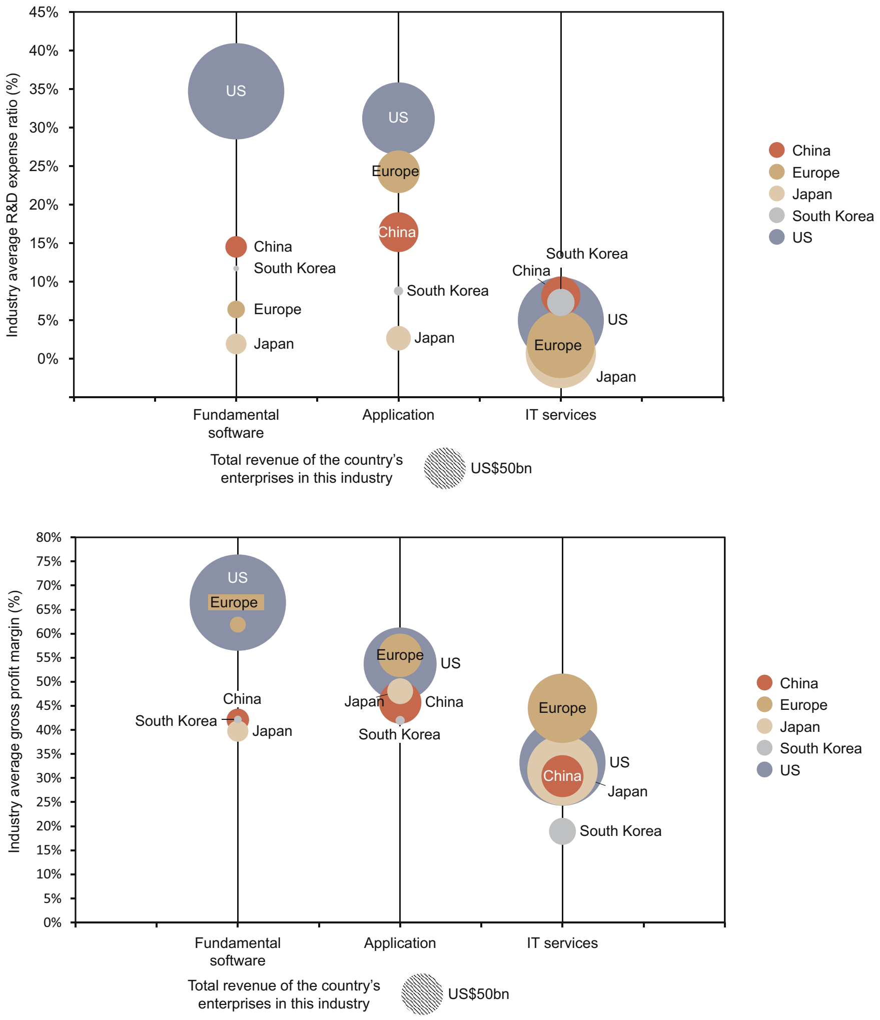

Fig. 1.24 Software industry value chain and R&D chain (2020). *Note* We selected 2,712 companies in the Bloomberg software and technical service sector in Western Europe, the US, China (including Hong Kong SAR and the Taiwan region of China), Japan, and South Korea for calculation. The size of the bubble represents the scale of revenue. *Source* Bloomberg, CICC Research Software Team

segment are still based on their high R&D intensity. In the EV battery value chain, Chinese companies have invested more in R&D in various segments and also enjoy higher gross margins than foreign companies (Fig. 1.25).

China's current dominant positions in the solar and EV battery industries mean that the country faces different value chain risks in these two industries from those in the digital economy. In the short term, China mainly faces export-related horizontal risk in the green economy. Some developed countries use anti-dumping and countervailing measures to impose sanctions on China's solar and other green industries. In the long run, the green economy should continue to thrive and the more critical technologies for achieving carbon neutrality are energy storage, hydrogen energy, and carbon capture. In these areas, which are of strategic significance to the green economy, China has not yet established advantages similar to those in solar and EV

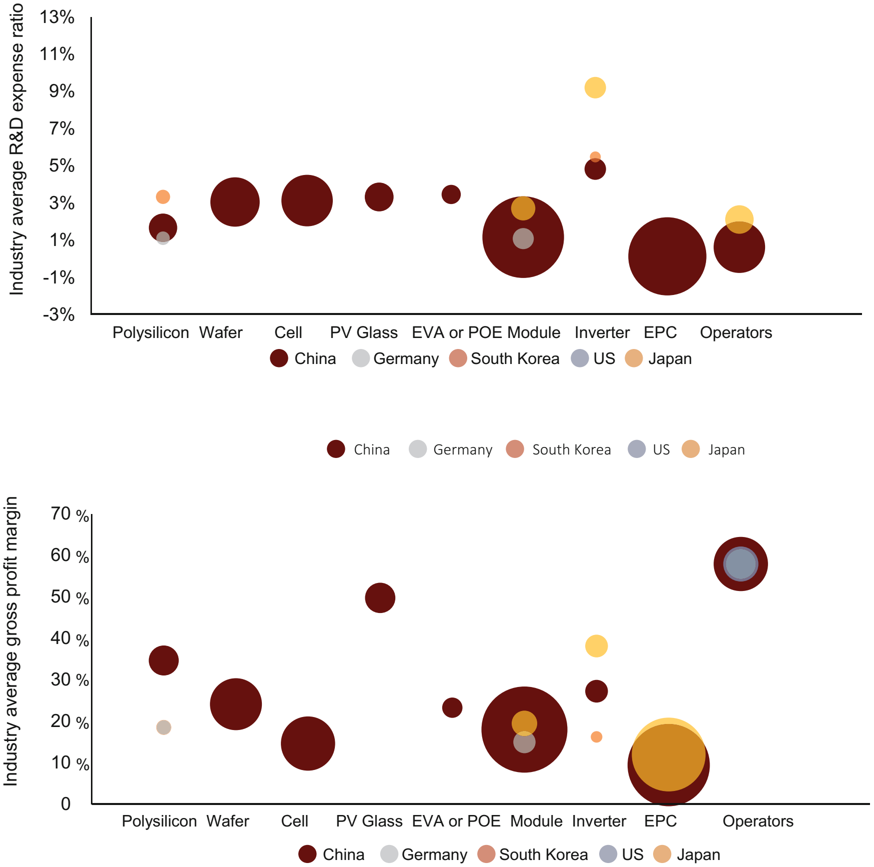

Fig. 1.25 Solar industry value chain and R&D chain (2020). *Note* Calculations are based on 2–3 leading companies in various segments of the solar industry in key countries and regions in 2020. Wind Info, Bloomberg, CICC Research Electrical Equipment and Utilities Team

battery industries. Major countries are all investing in R&D in these strategic areas. If other countries make breakthroughs first, China's advantages in the green economy could be significantly weakened, creating new vertical risks.

1.3.1.3 Bioeconomy: The US and Europe Are Highly Irreplaceable in the Seed and Pharmaceutical Industries

Generally speaking, the vertical risks faced by China in the bioeconomy are not as serious as those in the digital economy. China's import dependence on bioeconomy is concentrated in certain segments, such as soybeans and seeds in agriculture, and human vaccines and medical instruments in the pharmaceutical sector. Judging from the pharmaceutical value chain and innovation chain, areas with higher gross margins and irreplaceability largely have higher R&D intensity (Fig. 1.26). China has much lower R&D intensity than the US and Europe in the pharmaceutical manufacturing and medical device industries, which feature higher gross margins. In 2020, the top 10 US pharmaceutical companies by revenue invested 22.1% of revenue in R&D, while this proportion was only 14.3% for the top 10 Chinese pharmaceutical companies. In the agricultural sector, apart from fertilizers which are more like chemicals, other segments largely demonstrate a positive correlation between gross margin and R&D intensity. The segment with the highest gross margin and irreplaceability is seed production. China's R&D expense ratio in upstream seed production is only about 5%, much lower than the levels of 10–20% in the US and Europe. As a result, China has low gross margin and irreplaceability in this segment.

1.3.2 Innovation Economics for Improving Industry Chain Security

To sum up, the fundamental reason for industry chain risks caused by international competition lies in China's insufficient R&D investment and weak technological innovation capability. In this regard, we conducted a detailed analysis in the second section of this chapter to examine and compare China's intellectual innovation capability from multiple perspectives, including academic publications and invention patent applications.

There are two basic ways to accelerate technological innovation in China. One is to absorb technological spillover from advanced countries, and the other is to rely on indigenous innovation. On one hand, certain countries have implemented many restrictive measures against China in high-tech industries; on the other hand, these countries also need China to be integrated into the global industry chain to provide more efficient production. Over the past few decades, China has relied on both absorption of foreign technology and indigenous innovation, which complement each other.

Against the current background of international competition, China is facing an increasingly serious technological blockade, making it increasingly difficult to absorb advanced technological achievements from abroad. In fact, we believe international competition is determined by the objective strengths of countries, and is inevitable.

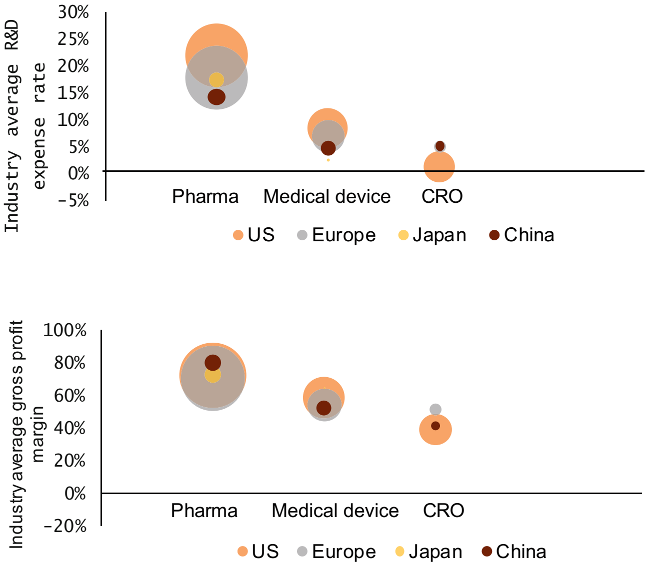

Fig. 1.26 Pharmaceutical industry value chain and R&D chain (2020). *Note* The size of the bubble represents revenue. The sample is the top 10 companies in the industry in the region. The Chinese pharmaceutical industry is ranked according to the pharmaceutical revenue of listed companies. As a reference, the top 10 companies in the US pharmaceutical industry have revenue of US$28.68bn. *Source* Wind Info, Bloomberg, CICC Research Pharmaceutical Team

In particular, technological competition holds the key to competition between major powers.

Although the US's expanding technology controls against China have indeed had an adverse effect on China's absorption of advanced foreign technology, this also forces Chinese companies to accelerate indigenous innovation, in our view. An empirical study shows that a China-US technology decoupling would lead to an increase in the patent output of Chinese companies in corresponding areas.[51] This shows that the foreign technology blockade is not only an "industry chain risk", but is also creating opportunities for spontaneous acceleration of China's scientific and technological progress.

Even if there is no external pressure from international competition, we believe China must strengthen R&D investment and accelerate technological innovation in order to achieve its medium- and long-term growth goals. The amended Communist Party of China (CPC) Constitution in the 19th National Congress of the CPC pointed out: In the new century and new era, the strategic goal of economic and social development is to create a "moderately prosperous society" in all respects by the centenary of the CPC (founded in 1921), and to build China into a modern socialist country that is "prosperous, strong, democratic, culturally advanced, and harmonious" by the

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[51] Han, P., Jiang, W., Mei, D. (2021). Mapping US-China technology decoupling, innovation, and firm performance. Innovation, and Firm Performance, 2.

centenary of the People's Republic of China (founded in 1949). In the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035, the goal is for per capita GDP to reach the level of moderately developed countries.

The above goals indicate that China's per capita GDP growth rate will need to be maintained at a relatively high level between 4% and 6% for a long period in the future. However, China's demographic dividend is fading. We expect China's working-age population will experience negative growth in the next 30 years. At the same time, since China's young and middle-aged population has crossed the growth inflection point in 2011 and is in a downward trend, the future savings rate is likely to continue to decline, leading to a gradual slowdown in capital accumulation. This means that in order to achieve China's medium- and long-term development goals, China's economic growth will rely more on total factor productivity (TFP) growth driven by technological progress.

At the same time, according to a study by Bravo and Marín (2011),[52] for middle- and high-income countries, every 1ppt increase in the intensity of R&D investment increases the growth rate of TFP by approximately 0.63ppt.

It should be noted that because different researchers have different understandings of relevant data and calculation methods, it is difficult for them to obtain uncontroversial conclusions for quantitative analysis of TFP and even economic growth. Therefore, our calculation results should be better understood as a quantitative analysis to express a qualitative conclusion, that is: In the current demographic situation, increasing the growth rate of TFP is a necessary condition for achieving mid- and long-term growth goals. Therefore, we believe it is necessary to increase the intensity of R&D investment. However, the more urgent question is how to achieve higher intensity of R&D investment and how to accelerate technological progress. We believe policy intervention is the key to these questions. As Nobel laureate Paul Krugman proposed in his new trade theory, for high-tech industries, the government needs to take appropriate intervention measures to foster innovation and gain long-term competitive advantages.

As for what specific policies should be adopted, this is a question to be answered by innovation economics. We conduct a systematic analysis of China's current state and challenges of technological innovation in Chapter 1 (including R&D resources and talent from the supply side and knowledge innovation achievements from the output side of innovation). Chap. 2 emphasizes the advantages that large scale brings about. China enjoys scale effect derived from the demand side of innovation, namely domestic consumption and international trade. The analysis of China's innovation economics is only the beginning, and is intended to guide our exploration of specific paths to accelerating technological innovation at the industrial level.

Chapters 3–6 constitute the industry-centered part of this report, mainly focusing on the application of innovation economics in industries of the real economy. On one hand, China needs to rely on technological innovation to improve its irreplaceability

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[52] Bravo-Ortega, C., Marín, Á. G. (2011). R&D and productivity: A two way avenue?. World Development, 39(7), 1090-1107.

in key areas, mainly including digital economy (Chap. 3), green economy (Chap. 4), and bioeconomy (Chap. 5). It should be noted that since different industries have different positions along the value chain and technological characteristics, the focus of innovation economics may vary in each chapter. Domestic demand has played a key role in the rise of China's solar and EV battery industries, but whether it remains important for future strategic technologies in fields such as energy storage, hydrogen energy, and carbon capture needs further analysis. For pharmaceuticals, at a time when China's commercial medical insurance system is not yet mature, whether the domestic industry can leverage its demand generated by foreign commercial insurance to accelerate its progress is an issue worthy of discussion. For agriculture, there is an urgent need to strengthen the protection of intellectual property rights and increase R&D intensity.

On the other hand, it is necessary to discuss manufacturing and logistics industries in particular. As mentioned above, the industrial basis for the formation of division of labor in the international industry chain is the transformation of manufacturing to the Wintel model and the sharp decline in logistics costs. China's large and complete manufacturing sector and well-developed logistics facilities are important advantages at the industrial level for the country to accelerate technological innovation. However, these two important pillars of innovation are "big but not strong." How should we view the roles of China's manufacturing and logistics industries in supporting innovation? What are the shortcomings to be overcome? What new opportunities do these two industries have to further strengthen their roles in supporting innovation? We will discuss these issues in Chap. 6.

Due to the positive externalities of innovation, the private sector is often less willing to support innovation, thus the public sector plays a major role in correcting market failures. Chapter 7 discusses how the government could build a national innovation system through coordinating and supporting technological innovation. The innovation system of a country includes not only market-based cooperation and interaction between enterprises, universities, and government, but also various innovation-related framework conditions such as infrastructure, policy framework, and macroeconomic environment. Regional innovation centers represent the main components of a country's innovation system. The rise of such innovation centers brings about concentration of innovation resources, and thus can boost the growth of local economies, create innovation-friendly environments, and facilitate the completion of a country's innovation targets. The chapter also stresses the importance of financing innovation. A common view is that external financial support is needed for innovation. The problem is that both real economy capital and financial capital are profit-seeking. If real economy capital is unwilling to provide financing for innovation, why is external financial capital willing to support innovation? In fact, according to our analysis of the relationship between finance and innovation in Chap. 7, financing does not spontaneously go to innovation, and financial intervention does not spontaneously promote innovation. Therefore, the government needs to contribute to innovation by financing through direct investment, system building, and credit enhancement.

Chapter 2
Size Matters: Economy-Wide Scale Effects

Abstract Size matters in an innovation economy. On the supply side, a large country usually has a higher GDP and large population. A higher GDP means that both its public and private sectors can commit more resources to innovation, hence higher R&D spending. On the demand side, a large population can contribute to large domestic demand. Domestic demand from large countries benefits innovation through economies of scale, economies of scope, and wealth effects. The first channel is through economies of scale. Demand from large countries helps reduce R&D costs per unit of output and enhances incentives for production-side R&D investment. Second, economies of scope can be better achieved through sizable demand, which also contributes to innovation. Diversified demand is conducive to the success of product differentiation strategies, which in turn encourages firms to increase their investment in innovation. Lastly, wealth effect affects consumers' participation in innovation, and also facilitates technological advancement. As consumers' spending power continues to improve, the proportion of consumers directly participating in innovation is also rising. This raises the overall investment in R&D resources.

In addition to domestic demand (consumption) and supply (R&D spending), international trade is also a key driving force for innovation. We believe trade can foster innovation via three channels: Economies of scale, learning, and competition. First, trade allows companies to expand business scale and generate more profit, which is conducive to diluting the fixed cost for R&D and innovation. Second, companies learn advanced technologies and improve production efficiency through trade. Third, international competition encourages innovation. In our view, the boost from learning is likely stronger when companies lag behind in technological knowhow, while the momentum from competition is likely more important for groundbreaking innovations.

However, changes in the external environment in recent years may pose challenges for China. We believe deglobalization, including trade protectionism, will hinder corporate development, and make it more difficult for companies to develop advanced technologies. The US has managed to lead key technological revolutions such as semiconductors, personal computers, and mobile internet. We believe this is because US companies have leveraged the global market to promote new products and

CICC Research, CICC Global Institute, *The Rise of China's Innovation Economy*,
https://doi.org/10.1007/978-981-99-8231-8_2

support high R&D spending, and kept improving themselves through international competition.

Despite changes in the external environment, we expect the rise of the digital economy to offer new opportunities through trade. Because of the replicability of data, the cost of data duplication is close to zero. Therefore, scale effects can be better leveraged in the digital world. We think the digital economy will also help improve human resources and talent development, strengthen the scale effect, and thus benefit technological innovation. We think the digital economy can help expand the scale of trade in both goods and services, and enable more companies to benefit from trade.

Digital economy also offers new opportunities in demand-driven innovation. We expect the digital economy to accelerate consumption-led innovation. In a digital economy, products and services are more closely integrated, further underscoring the importance of local demand. Big data helps companies effectively understand consumer needs and facilitate technological innovation. A digitalized economy provides consumers with new models of product innovation for consumer goods. A digital economy also reduces the cost of consumer participation in technological innovation and helps increase the proportion of consumers participating in innovation.

2.1 Large Countries Have Advantages in Innovation

Size matters in an innovation economy. Large countries have various advantages, including large R&D spending by both the government and the private sector, and large domestic demand that comes with a large population, which in turn could stimulate consumption-led R&D. Furthermore, large countries are more prominent in international trade, which also helps foster innovation.

2.1.1 Size Matters in R&D Spending

Large economies enjoy natural advantages in R&D spending. Figure 2.1 shows changes in R&D spending of major innovative countries across the globe, indicating that technology powerhouses such as the US and China have invested much more in R&D than other countries.

Having the highest level of R&D expenditure in the world is an important reason why the US led global innovations after World War II. According to the Organization for Economic Co-operation and Development (OECD), the US's annual R&D expenditure in the 1980s was almost half of the aggregate R&D spending of other major countries and approximately four times the R&D spending of Japan, which is also an innovative country. The US's share of global R&D spending remained at around 30% until 2018, and contracted amid rapid expansion of Chinese R&D

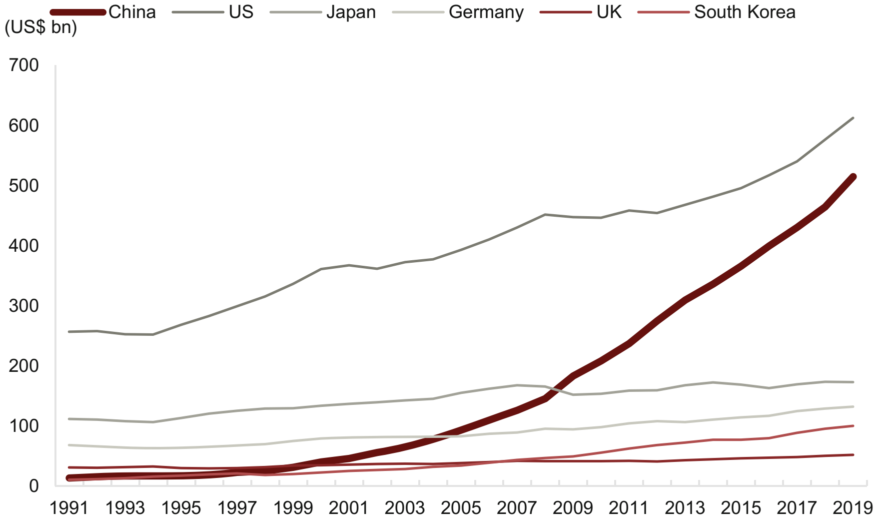

Fig. 2.1 The US and China's R&D spending has significantly exceeded the spending in other countries. *Source* OECD, CICC Global Institute

investment (Figs. 2.2). The US federal government budget report for 2020 listed a wide range of technological projects in the areas of national defense, public health, energy, aviation and aerospace, agriculture, and the environment and climate. The report also outlined R&D projects on network and information technologies as well as cross-institution projects that focus on frontier technologies such as the national nanotechnology program.[1]

China's massive R&D spending is very helpful for spurring innovation. First, the size of the spending affects the probability of innovation success. High R&D spending makes it possible to explore multiple technological options, and increases the probability of making breakthroughs. The success of science R&D is accidental, and requires exploration of multiple options. High spending and ample human resources can facilitate simultaneous exploration of these multiple options, and ensure a higher tolerable error rate. For example, in the process of pharmaceutical R&D, companies that cover a large number of therapies tend to have good achievements.[2] In the Manhattan Project, the major technological option for the R&D of atom bombs was uranium fission, but the simultaneous exploration of plutonium fission reaction paved the way for final success. We believe a larger R&D network is more helpful in attracting resources, promoting knowledge-sharing, enhancing R&D returns, and diluting R&D spending per unit of product.

Second, a country can solve global problems by embarking on large R&D projects. The world now faces a number of serious challenges such as climate and

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[1] Federal Research and Development (R&D) Funding: FY20.

[2] Cockburn, I. M., Henderson, R. M. (2001). Scale and scope in drug development: unpacking the advantages of size in pharmaceutical research. Journal of health economics, 20(6), 1033-1057.

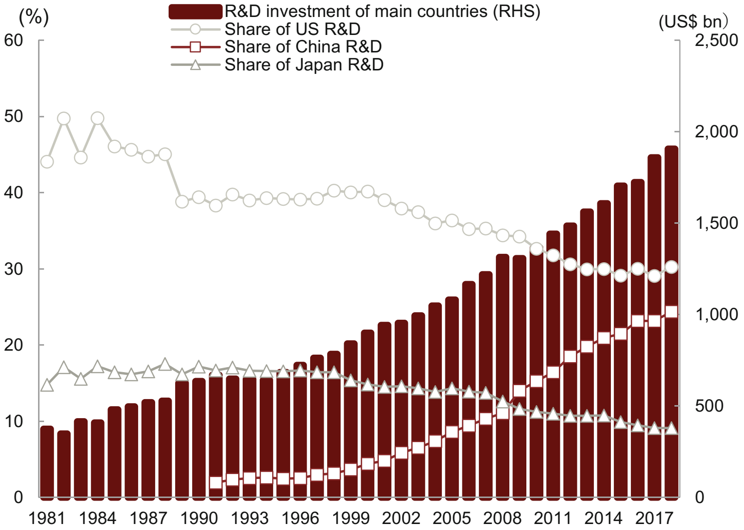

Fig. 2.2 The US of global R&D spending has remained larger than that of other countries. *Source* OECD, CICC Global Institute

energy issues. Successfully combating these challenges requires worldwide cross-disciplinary cooperation.[3] As overcoming these challenges requires ample human resources and heavy spending, larger economies enjoy competitive advantages over their smaller counterparts. For example, the EU earmarked EUR3.8bn in 2014–2020 to fund the Horizon 2020 program that focuses on R&D of clean energy technologies.

2.1.2 *Large Domestic Demand Benefits Innovation*

Innovation is an economic activity with positive externalities. Either increasing the economic returns of innovative activities or reducing the cost of innovative activities enhances the motivation of innovative activities. In both these aspects, demand in large countries plays a positive role. Compared to small markets, the large markets in large countries bring advantages in three aspects: Economies of scale, economies of scope, and wealth effects.

Economies of scale improve efficiency of innovation. Demand from large countries is reflected in their large populations, but more importantly, in large spending power. We believe a large country's demand is mainly reflected in the country's

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[3] Præst Knudsen, M., Tranekjer, T.L Bulathsinhala, N. (2017). Advancing large-scale R&D projects towards grand challenges through involvement of organizational knowledge integrators, industry and innovation, Gould, M. "GIScience grand challenges: How can research and technology in this field address big-picture problems?" ArcUser, 13(4), 64–65.

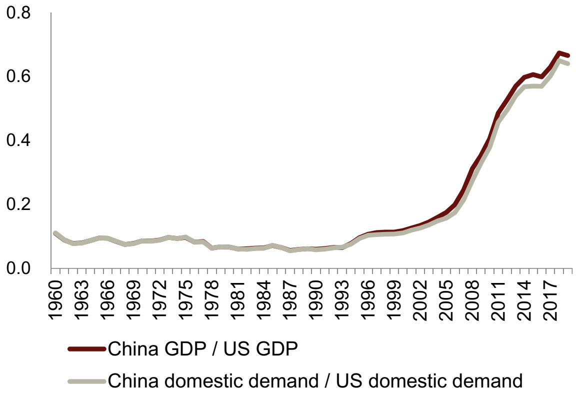

Fig. 2.3 Ratio between China and US GDP and their domestic demand. *Source* Wind, CICC Research

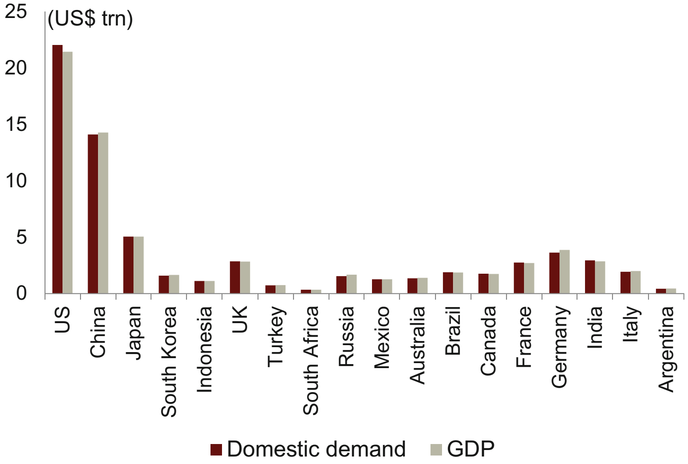

Fig. 2.4 Domestic demand and GDP of G20 countries (2019). *Source* Wind, CICC Research

domestic demand supported by its population.[4] China's domestic demand is equivalent to around 64% of demand in the US in 2019—a significantly higher proportion than from other countries (Fig. 2.3). As the domestic demand of each G20 country accounts for more than 90% of its GDP in 2019, we use GDP to measure macro-level demand and GDP per capita to measure income per capita in the analysis below (Fig. 2.4).

The economies of scale for innovation created by a large country's demand are mainly reflected in two aspects—i.e., "learning-by-doing" and the sharing of R&D

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[4] The domestic demand mentioned in this chapter refers to the sum of consumption, investment, and government expenditures in GDP calculated through the expenditure approach.

costs. Learning-by-doing plays an important role in the production processes of technological innovation. To a degree, even if inputs of R&D and human resources are not intentionally increased, repeated production activities alone could also lead to efficiency improvement and technological advances. Such a learning-by-doing mechanism is only effectively realized with demand in large countries.

More importantly, the large-scale production supported by the demand in large countries can reduce the unit R&D cost of products and improve overall motivation for R&D at companies. Consumer demand accounts for the main part of domestic demand. China has the world's second largest consumer market in 2021.[5] In 2019, China's retail sales reached US$6trn,[6] much higher than developed countries such as the UK, Germany, and Japan, and second only to the US. The gap between retail sales in China and the US is narrowing, and we believe that China will likely become the world's largest retail market in the future.

Economies of scope increase intensity of R&D investment. Economist Paul M. Romer believes that monopoly profit is the engine of market R&D[7] as the excess earnings generated by monopolies are to a degree the internalization of the positive externalities of innovation. Product differentiation through innovation at companies is an important method for obtaining monopoly profits. The success of this supply-side differentiation strategy depends on whether the demand side has sufficiently diversified demand. Research shows that the diversity of consumer preferences encourages firms to innovate to meet the needs of different consumers; once companies find such needs in the market and apply them to R&D and production, innovation pays off better.[8]

China has a large population with diverse consumer needs. The 2020 censuses in China and the US show China's population at 1.41bn and the US population at 333mn. China's large population induces the complexity and variety of consumer needs as well as diverse market segments in the country. In China, the combined market shares of top brands in major consumer-related industries such as clothing, food, housing, and transportation are lower than they are in the US, underscoring the diversity of demand in China (Fig. 2.5). Amid diverging consumption in different market segments, companies are gradually exploring needs and promoting innovations for specific consumer groups and scenarios. Innovations spring up in specific market segments of industries such as F&B, catering, and automobiles. For example, eating habits vary greatly in different regions of China, resulting in fragmented market shares in various segments of the country's catering market (Fig. 2.6).

Some studies claim that diversified demand could reduce the market size of specific products, although it increases the number of submarkets. This would reduce

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[5] Source: Ministry of Commerce. https://www.gov.cn/xinwen/2021-08/24/content_5632898.htm [Chinese only].

[6] Source: National Development and Reform Commission.

[7] The Committee for the Prize in Economic Sciences in Memory of Alfred Nobel (2018). Economic growth, Technological Change, and Climate Change.

[8] Lancaster, K. (1966). Change and innovation in the technology of consumption. The American Economic Review, 56(1/2), 14–23.

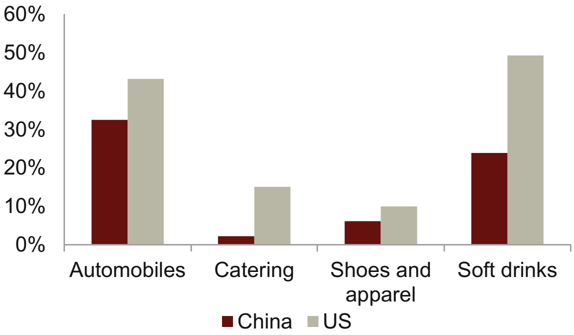

Fig. 2.5 Combined market shares of top three brands in major consumer-related industries in China and the US (2020). *Source* Euromonitor, Marklines, CICC Research

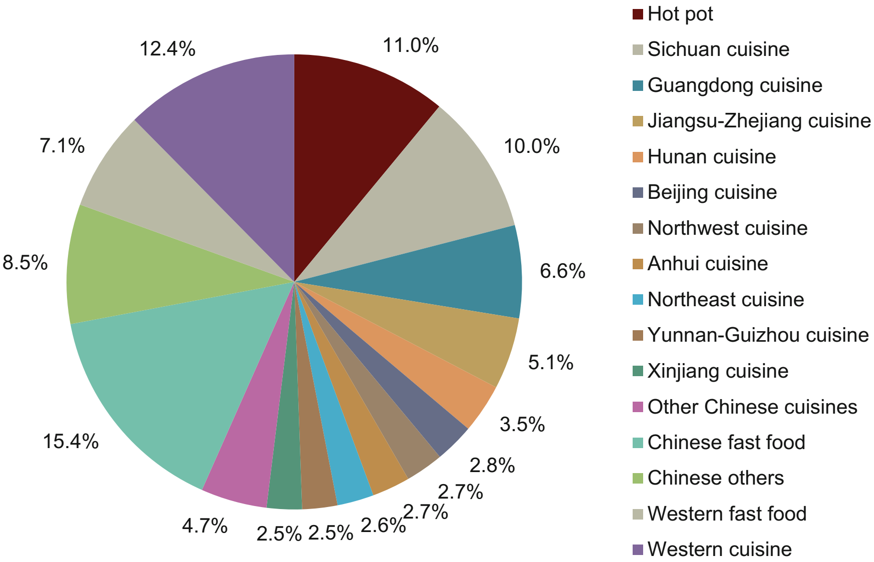

Fig. 2.6 China's catering market has many different segments. *Note* Data based on 2017 revenue. *Source* Frost & Sullivan, CICC Research

the earnings incentives in specific markets, thereby adversely affecting innovation.[9] The adverse effects of diversification further underscore the economies of scale created by demand in large countries. China has a population that is more than three times the population of the US. Even a small market segment in China has a larger number of consumers on average than in the US. The sizeable diversified demand in China has eventually produced economies of scale that are conducive to innovation.

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[9] Guerzoni, M. (2010). The impact of market size and users' sophistication on innovation: the patterns of demand. Economics of Innovation and New Technology, 19(1), 113–126.

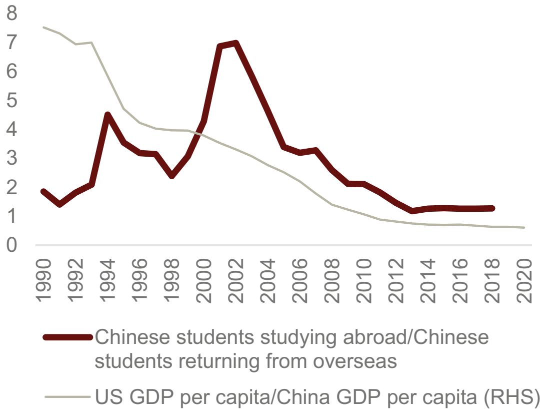

Fig. 2.7 Ratio of US GDP per capita to China GDP per capita; the ratio of Chinese students studying abroad to the number returning home. *Source* Wind, CICC Research

For example, although JD.com and Alibaba are the leading e-commerce platforms in China, Pinduoduo manages to thrive by relying on consumers in tier-3 and tier-4 cities and rural areas, showing that the diversity of demand in large countries has a positive effect on innovation.

Wealth effects promote input of supply-side resources for innovation. Supply-side resources such as R&D and human resources are crucial to the innovation process, but the input of supply-side resources also depends on demand. For example, the GDP per capita of the US once used to be more than 30 times that of China's. The number of Chinese students studying abroad then substantially exceeded the number of Chinese students returning home (Fig. 2.7). China had relatively low income levels then, and it was difficult to attract talent. This led to a significant outflow of skilled labor. However, as the gap in per capita GDP between China and the US narrows and domestic demand becomes a main driver for economic growth, China's attractiveness for skilled labor has improved since 2003, and the ratio between the number of Chinese students studying abroad and the number of Chinese students returning home has been declining quickly.

R&D investment is a similar situation, and at the micro level, it reflects consumer participation in innovation. Consumer participation in innovation refers to the technological innovation by consumers through independent design & production, cooperation with companies, or open-source cooperation in R&D as well as product innovations. Consumer innovation can result in R&D spending such as spending on material purchases, mailing, and tool purchases. Thus, consumer willingness to innovate R&D resources is also highly correlated with per capita GDP (Fig. 2.8). Research by Eric von Hippel shows that in some developed countries, consumer investment in technological innovation exceeds investment in business.[10]

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[10] Von Hippel E et al., (2010). Comparing business and household sector innovation in consumer products: Findings from a representative study in the UK, CICC Research.

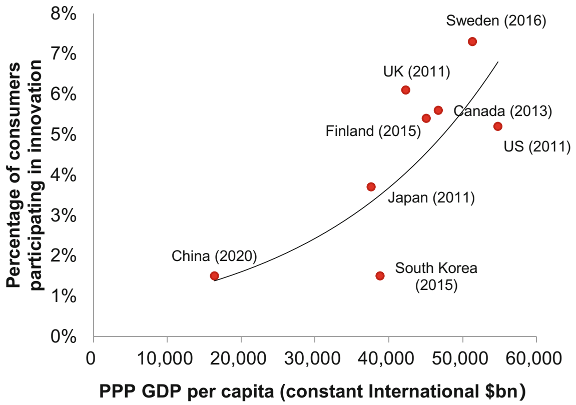

Fig. 2.8 Percentage of consumers participating in innovation; per capita GDP in select countries. *Source* Sichel et al., Household Innovation and R&D: Bigger than You Think, the review of income and wealth, October 2020; Chen et al., Household sector innovation in China: Impacts of income and motivation, Research Policy, May 2020., CICC Research

2.1.3 How International Trade Facilitates Innovation

In addition to domestic R&D demand and R&D supply, international trade is also a key driving force to innovation. International trade also promotes innovation through economies of scale, learning, and competition, highlighting the importance of scale effects. The development of information technology reduced the communication cost between companies in the past four decades. International trade gradually transformed from traditional inter-sector and intra-sector trade to a cooperative production model based on a global value chain. Under this model, traditional "trade of goods" is replaced by "trade of tasks", and companies only need to focus on one part of the production process and one specific task.

Under the global value chain system, we believe that engaging in international trade will benefit innovation. Numerous studies have shown that companies engaged in international trade are likely to have higher production efficiency and stronger capability and willingness for innovation. Data shows that export companies in China have a higher number of patent applications and approvals than non-exporting ones (Fig. 2.9). This is especially true in technology-intensive manufacturing sectors such as instruments and apparatuses, electrical and machinery equipment, and transportation equipment.

How does international trade promote innovation? Past research shows there are three mechanisms: Economies of scale, learning, and competition (Fig. 2.10).

First of all, economies of scale play a central role. International trade allows companies to expand markets and generate more profit, which is conducive to diluting fixed cost for R&D and innovation. According to the Schumpeterian hypothesis, companies with higher profit are more incentivized to innovate. In addition, these companies are likely to spend the gains from international trade on R&D to improve

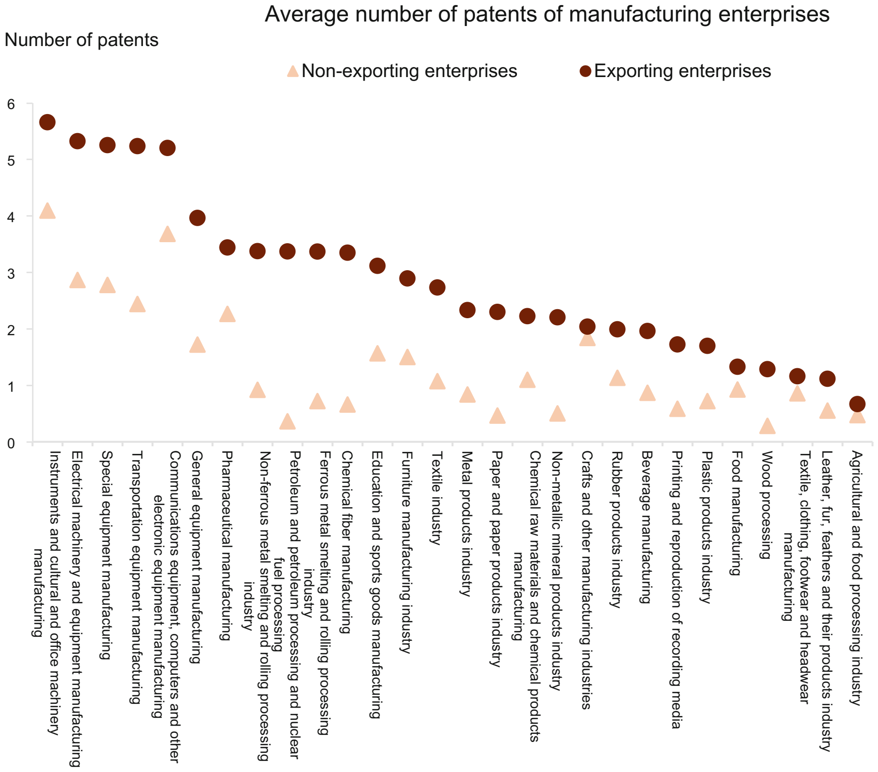

Fig. 2.9 Export companies in China have a higher number of patent applications and approvals than non-export ones. *Note* (1) Number of patents includes both applications and approvals; (2) we winsorized 5% of the data. *Source* Chinese industrial enterprises database (2012), China innovative enterprise data base, CICC Research

the competitiveness of their products globally. This creates a positive cycle in which exports and innovation reinforce each other.

Another important mechanism to promote innovation through international trade is learning. Through international trade, companies learn advanced technologies and improve production efficiency. Specifically, companies can learn via exporting, importing, and foreign direct investment. First, companies learn via feedback from foreign clients—i.e., "learning by doing." Second, companies learn from importing intermediate goods technologies and expertise. Third, studies show that foreign direct investment produces positive spillover effect both horizontally (via employees) and vertically (via upstream and downstream) along the industry chain, boding well for innovation by domestic companies.[11]

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[11] Wang, C., Zhao, Z. (2008). Horizontal and vertical spillover effects of foreign direct investment in Chinese manufacturing. Journal of Chinese economic and foreign trade studies, 1(1), 8–20.

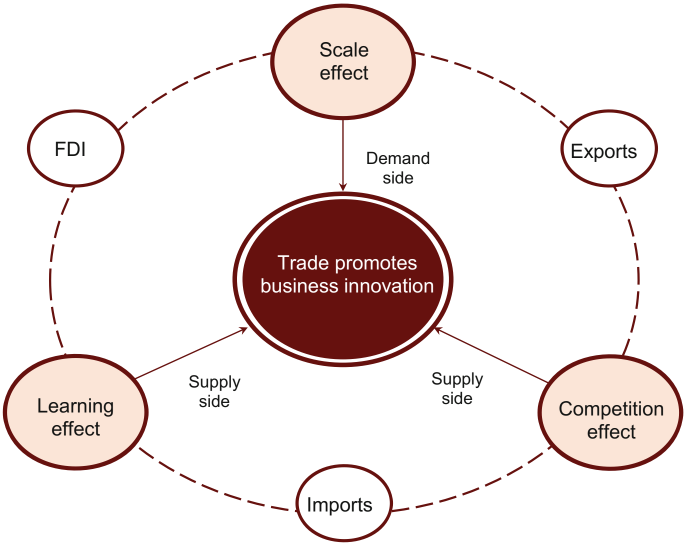

Fig. 2.10 How international trade promotes innovation. *Source* CICC Research

Thirdly, international competition encourages innovation. Full competition helps screen companies, and enables efficient and innovative firms to seize more market share (i.e., the pro-competition effect). These companies are likely to gain higher market share and profit, which may facilitate innovations and allow these companies to remain competitive.

In sum, economies of scale focus on the role of demand, while learning and competition emphasize the role of supply. In addition to gaining higher market share and profit through trade, we believe it is more important to learn from and compete with strong names via trade to accomplish constant self-improvement and maintain strong positions.

As China catches up and gradually becomes a frontrunner in certain technologies, we expect the role of learning to wane and the role of competition to become more important. That said, we think economies of scale are crucial in each and every stage of development, stressing the significance of large scale. Unlike Western developed economies, modern industrialization started late in China, and China had been learning and catching up for a long time. At one stage, advanced global technologies were not accessible to most Chinese companies, and technological innovations in China were mainly driven by learning from overseas advanced technologies. However, more and more domestic sectors have become leaders in global technologies in recent years thanks to accelerating technological advances in China. As a result, a rising number of Chinese companies have become creators of groundbreaking innovations. These companies have become not so much learners as competitors with advanced global companies. Such competition encourages them

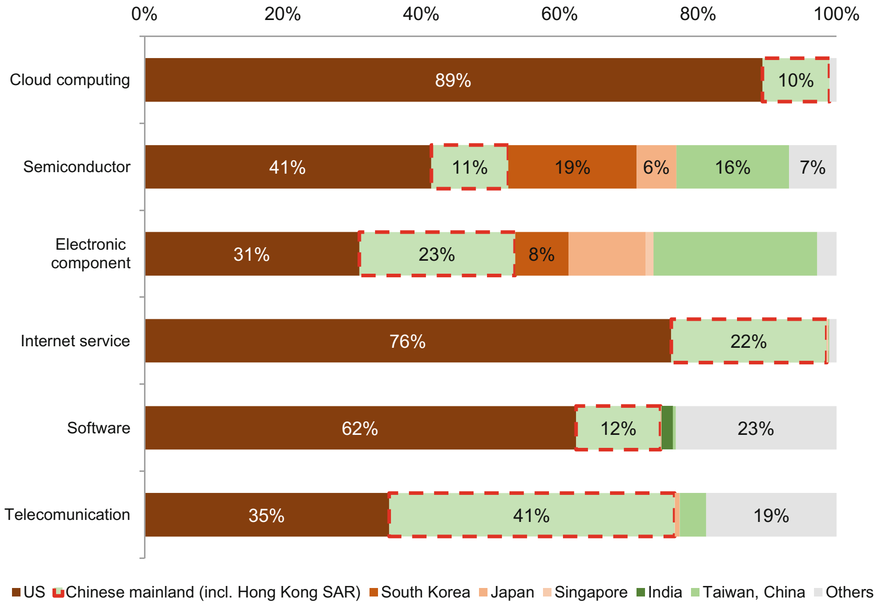

Fig. 2.11 Revenue distribution of global technology sectors (2019). *Source* Wind, Bloomberg, CICC Research

to innovate, boding well for improving production efficiency.[12] Research shows that for companies at the forefront of technologies, more intense competition tends to result in lower profits and thus more incentive for these companies to seek excess profit through innovation, contributing to the "escape-competition effect".[13]

Which Chinese sectors are at forefront of global technologies? Thanks to over three decades of development, China has gained certain advantages in technologies such as 5G, artificial intelligence (AI) applications, and hardware manufacturing. In addition, a number of innovative companies have emerged. For internet service, select Chinese companies have become globally competitive. However, China still lags behind the US in semiconductors, software, and cloud computing (Fig. 2.11).

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[12] Aghion, P., Blundell, R., Griffith, R. et al., (2009). The effects of entry on incumbent innovation and productivity. Review of Economics and Statistics, 91(1): 20–32.

[13] Aghion, P., Blundell, R., Griffith, R. et al., (2009). The effects of entry on incumbent innovation and productivity. Review of Economics and Statistics, 91(1): 20–32.

2.2 Digital Economy Offers Opportunities Amid New External Environment

While large countries benefit from scale effect in innovation, the external environment has changed significantly in the past two years, and "deglobalization" may weigh on corporate operations, investment, and innovations, in our view. The US government has since 2018 adopted a series of trade protectionist measures such as imposing additional tariffs on goods imported from China, and including Chinese companies in its "Entity List."

US government has also tightened reviews of the industry chain. The US government in June 2021 released a 250-page "100-day supply chain review report" that covers a wide range of industry chains such as semiconductors, batteries, key raw materials, and pharmaceutical manufacturing. We note the 100-day supply chain review report mentioned China 341 times, many more times than other major trading partners or competitors of the US such as Japan (70), South Korea (58), Canada (37), Germany (18), and Russia (7).

Despite changes in the external environment, we expect the rise of the digital economy to offer new opportunities (Fig. 2.12). The replicable and non-rival features of data better facilitate economies of scale, in our view. As a result, digital transition can boost innovation through international trade, and promote more consumption-led innovations in the digital era.

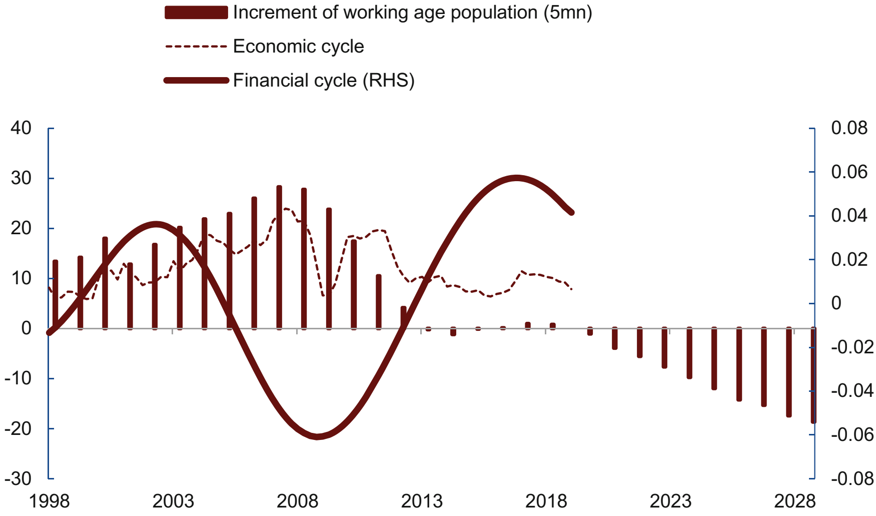

Fig. 2.12 Next decade in China: digital economy. *Note* Economic cycles are based on nominal GDP and one unit on the left axis represents 1%. *Source* Wind, United Nations Population Division, CICC Global Institute

2.2.1 Digital Economy Boosts Innovation from Trade

We believe the digital economy will improve economies of scale and enhance the boost from learning and competition, thus strengthening the momentum of innovation from trade. We think the digital economy can help expand the scale of trade in both goods and services, and therefore foster innovation. In our view, the digital economy can strengthen growth momentum from learning, and contribute to more corporate innovation under a similar scale of trade. We also expect the digital economy to stimulate competition, and facilitate companies' upgrading towards the parts of the global industrial value chain with higher added value.

We believe trade can promote innovation via three channels, but they affect different companies to varying degrees. We believe the boost from competition is stronger for leading Chinese companies as they already enjoy a high market share, and supply-side self-innovation is thus more important. Meanwhile, we believe the momentum from economies of scale is more important for other companies as they rely on further profit growth to spur innovation, and demand-side pull is crucial.

Apart from the boost from economies of scale, learning, and competition, we think the digital economy can also help improve human resources and talent development. For trade to stimulate innovation in the end, we believe human resources should also play a key role. Amid changes in the global center of economy and technology, human capital first flowed to Europe before flowing to the US. This enabled the US to surpass Europe to become the world's largest center for innovation. We believe China can become a center for innovation in the digital-economy era if it can: 1) Take full advantage of high-quality learning resources across the world and turn its advantages in population into competitive edges in talent; and 2) utilize overseas talent resources to boost domestic innovation.

2.2.1.1 Digital Economy and Economies of Scale

While trade protectionism may weigh on select companies, we think the digital economy can improve trade conditions, increase the scale of trade, and thus stimulate innovation. We believe the digital economy will enable more companies to trade, especially small- and medium-sized companies. On the demand side, the digital economy helps expand the regional coverage of trade, reduce trade barriers, and enhance efficiency in matching. On the production side, the digital economy facilitates coordination and corporate decision making. Specifically, we think digital technologies can mitigate the restrictions in time and space, and make more trade in services possible.

From the demand side, we think the digital economy can reduce cost of trade. The cost of trade mainly comes from distance (such as transportation cost, trading cost, and contract cost) and cultural differences (such as costs arising from differences in languages and legal systems), in our view. We think the digital economy can significantly reduce the cost of trade and increase the scale of trade. Research shows a 1% increase in distance reduces trade volume by 1–2% in traditional trade, but the drop is milder at 0–0.5% in a digital economy.[14] Meanwhile, a 2019 study on eBay found machine translation helped increase US exports to Latin American countries by 17–21%.[15]

In addition, the digital economy can improve efficiency of matching. The difficulty in matching buyers and sellers restricts the market coverage of companies, but we believe digital technologies can provide more useful information, reduce the cost of matching, and thus improve matching efficiency. Research[16] shows that merchants with ratings have 25% higher revenue on average than merchants without ratings in cross-border e-commerce.

From the production side, we think the digital economy can enhance efficiency in coordination. We expect digital technologies to facilitate coordination along the value chain, and the industrial internet to improve matching between producers and suppliers. We believe digital technologies can also strengthen coordination within companies. For example, a large number of companies turned to digital tools such as the software company Zoom for business coordination during the pandemic, which helped lower communication costs and mitigate the negative impact of COVID-19 on corporate operations.

In addition, digital economy can assist in corporate decision making. We expect digital technologies to help companies identify consumer demand and better target their clients on the back of big data analysis. This bodes well for improving flexibility in decision making, in our view. Research[17] shows that more market information bolsters corporate sales growth.

For service trade, we think digital economy can also improve tradability of services. Service products usually require face-to-face transactions between producers and consumers, and sometimes even real-time transaction is needed. However, we expect the digital economy to remove such restrictions. For example, online platforms allow for things like remote teaching and video-based remote medical diagnosis. We expect tradability of technology-intensive services such as education and healthcare under the digital economy to improve (Fig. 2.13). Meanwhile, new generations of telecom technologies such as 5G further raise the speed of data transmission and allow more service products to become tradable.

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[14] Lendle, A., Olarreaga, M., Schropp, S.et.al. (2016). There goes gravity: eBay and the death of distance, The Economic Journal, 126(591), 406–441.

[15] Brynjolfsson, E., Hui, X., Liu, M. (2019). Does machine translation affect international trade? evidence from a large digital platform, management science, 65 (12), 5449–5460.

[16] Chen, M. X., Wu, M. (2020). The value of reputation in trade: Evidence from alibaba, The Review of Economics and Statistics, 1–45.

[17] Luohan Academy, (2020). Understanding big data: Data calculus in the digital era.

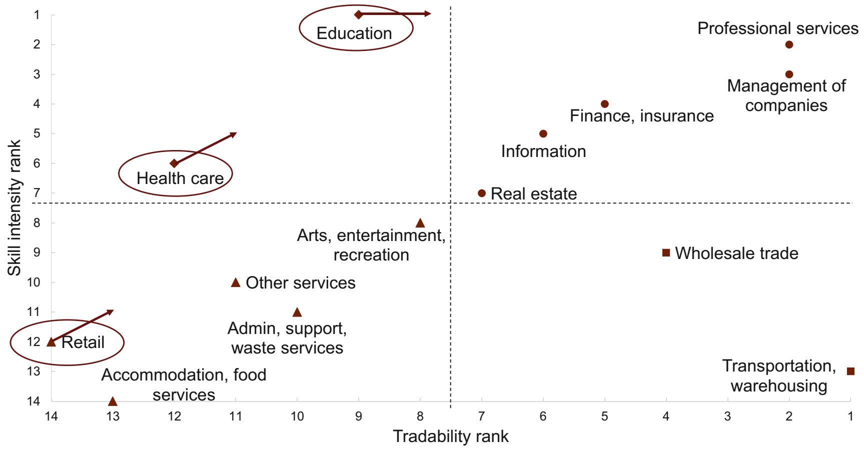

Fig. 2.13 Digital economy improving tradability of services. *Note* Technology intensity is based on the proportion of employees with post-graduate educations, while tradability is measured by (import value + export value)/total sector output. *Source* Eckert, F., Ganapati, S., & Walsh, C., Skilled tradable services: The transformation of US high-skill labor markets, 2019., CICC Research.

2.2.1.2 Digital Economy and Learning

In addition to amplifying the technological spillover from trade and foreign direct investment, we think the digital economy will also expand channels for companies to learn from advanced knowledge and technologies. This will stimulate corporate innovation, in our view.

Digital technologies help to improve technological spillover from trade. Through trade, companies acquire technology and knowledge via feedback from export clients, learning from imported intermediate goods, and the benefiting from the positive spillover of foreign direct investment (FDI). For example, professional consulting services and analysis of data on sector imports, exports, and FDI are likely to help companies better understand sector development trends, optimize product structure, and improve mode of trade. In addition, digitalization of professional knowledge and internet communications should facilitate analysis of product components and related discussion on R&D, thus benefiting corporate innovation.

Furthermore, digital economy also optimizes the mode of learning. Path dependence may prevent companies from dealing with R&D challenges if they only rely on in-house R&D staff to do so. However, we think global knowledge sharing platforms will help address this issue. They not only expand the pool of knowledge and ideas, but also contribute to increased diversity as knowledge and ideas may come from people in different parts of the world with different ways of thinking. This should improve the chances of success, in our view. For example, InnoCentive is an online platform for innovation resources, and it boasts over 500,000 registered users from about 200 countries and regions. It allows companies to post the unsolved problems and unmet needs of their R&D activities on the platform in the form of challenges; it invites users across the world to offer their solutions and provides reward for qualified solutions.

2.2.1.3 Digital Economy and Competition

We think the digital economy can empower companies and improve their competitive edges. However, we also believe the digital economy can have a contrasting impact on producers along the global industrial value chain.

On one hand, we believe the digital economy may reduce the added value of production and make it harder for companies in the middle of the industrial value chain to move to the two ends with higher added value. The digital economy can change the relative importance of factors of production, and mechanization is likely to reduce the value of low-cost human resources. As a result, technology-intensive sectors with high added value may flow back to developed countries from developing countries. This may squeeze the added value of developing countries along the industrial value chain, in our view. The curve of value distribution along the industrial value chain may thus become steeper, boding ill for innovation by producers because a lack of incentives from profit may discourage them from innovating.

On the other hand, we also think the digital economy can also empower producers and facilitate their upgrading at the two ends of the industrial value chain. Data is an underlying asset for the digital economy, and it has zero marginal cost but enormous economies of scale as well as network effect. In international trade, intermediate producers can leverage big data to target clients more precisely and obtain market feedback faster. We also expect the digital economy to enhance companies' learning capabilities. This should facilitate their expansion towards R&D, design, marketing, and other parts of the industrial value chain with higher added value, and help them secure a better position in the global market, in our view. In addition, we think companies can also explore hidden knowledge with technologies such as machine learning, and thus expand their knowledge base. Supported by big data, machine learning can identify overlooked information in design and production, and enable companies to differentiate themselves in production. This should contribute to a flatter curve of value distribution along the industrial value chain. We think this bodes well for innovation by producers because they are likely to have more profit to invest in innovation.

2.2.1.4 Digital Economy and Talent

Human capital is crucial for innovation. Over the past century, the destination of global human capital flow shifted from Europe (e.g., Germany and the UK) to the US, which has grown into a global center of innovation driven by the rapid development of its high-tech sectors supported by top-notch international talent. Research shows that people born outside the US account for a higher proportion of US patents, and their patents are more important in technologies and value than the patents contributed by people born in the US.[18]

For China, we think the digital economy can help turn the country's advantages in population into competitive edges in talent, therefore laying a solid foundation for innovation. Digital economy can accelerate the accumulation of human capital. We think distance education and digital platforms can speed up the spread of knowledge. For example, students can remotely access courses at universities worldwide thanks to online education. We note the cumulative page views for open courses from the Massachusetts Institute of Technology from Chinese users is lower than from English-speaking countries such as the US and India, but page views would significantly increase if we take into account such foreign courses hosted on domestic online platforms. Therefore, we believe digital platforms can help overcome language barriers, and accelerate the spread of knowledge. In addition, we think digital platforms help Chinese human capital access top-notch overseas resources. That said, average page views at both MIT and at domestic online platforms for Chinese people with postgraduate degrees are still at an average global level, implying large upside potential for utilizing overseas resources. Furthermore, digital transformation can facilitate the collision of ideas. For companies, we think digital platforms and technologies help pool global talent for R&D activities and brainstorming for decision making. For schools, we believe digital platforms and technologies can facilitate academic communication, thus mitigating geographical restrictions on the exchange of ideas and boosting innovation.

2.3 Consumption-Led Digital Innovation in Large Countries

We believe that the digital economy can enhance the role of innovation with sizable demand in large countries. Local demand is important in the digital era as it gives rise to scale effect. Digital technologies help bring about a better understanding of consumer needs and provide new ways for consumers to take part in innovation.

2.3.1 Digital Economy Accelerates Consumption-Led Innovation

Products and services are more closely integrated in a digital economy, further underscoring the importance of local demand. Simon Kuznets has proposed different development models for large and small economies. He believes that large economies have comparative advantages in independent development and innovation and can achieve

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[18] No, Y., Walsh, J. (2010). The importance of foreign-born talent for US innovation, Nature biotechnology, 28, 289–291.

Schumpeterian growth, while small economies rely on specialized earnings generated by free trade, namely Smithian growth.[19] Kuznets's ideas are based in an era in which manufacturing played a dominant role. However, in the digital economy, an important feature is that demand increasingly exists in the form of digitalized services; the tradability of services is poor. Thus, localized services are particularly important for product innovation.

This means that the advantages of the Schumpeterian growth model for large countries based on local demand are likely to become more obvious than in the Smithian growth model for small countries. A significant number of products featuring technological innovation would eventually rely on localized services to reach consumers. Localized service demand reduces the speed of overseas innovative products entering the Chinese market. Domestic companies focusing on technological innovation can seize opportunities from the time lag to catch up with their counterparts. They can rely on their advantages in services to compete with overseas firms in the near term and gradually catch up with overseas companies in technology.

The case of smart speakers is a good example of the importance of the local market. The Amazon Echo smart speaker was launched in 2014, and it became popular globally thanks to its superior interactivity and open systems. Given China's significant local market, tech giants such as Alibaba entered the smart speaker market in 2017, and Alibaba has become a leader in the Chinese smart speaker industry. Smart speakers are not essentially a hardware business, and providing quality service is key. Although the Echo features advanced technologies and superior performance, the smart speaker still uses English to interact with users in China. Echo mainly connects with foreign platforms such as Spotify, Pandora, and Amazon Music, and cannot provide localized services in China. Thus, China's local smart speaker products such as the Tmall Genie can succeed in the domestic market thanks to their lower prices and more localized services.

Big data helps firms understand consumer needs and facilitates technological innovation. Improved efficiency guiding supply-side innovation through the demand side depends on the supply side's grasp of demand. In the digital economy, the effects of big data on innovation are mainly reflected in companies having larger amounts of data and a better understanding of the needs of consumers, thereby enabling them to promote innovation. China has well-developed e-commerce platforms, and the penetration rate of online consumption is high. Each user of e-commerce platforms is an individual with personal characteristics and an awareness of social media. Internet firms can access information on consumer preferences by noting the user's browsing habits.

Douyin, with its A/B algorithm, helps better assess user needs. Douyin is a short video platform based on big data and intelligent algorithms. It adopts a single-column model to display content, emphasizes an immersive user experience, and has high requirements for content quality. Thus, the platform requires highly accurate algorithms. Douyin adapted to user needs in its initial stage, and the platform has evolved

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[19] Ouyang, Y., Tang, L. X.(2017).The economic explanation for the innovation paths of large countries, Economic Research Journal.

to meet more precise user needs thanks to its frequently updated and upgraded A/B algorithm. The process of the algorithm is divided into three parts: Labeling content, labeling persons, and recommending individualized content to users based on the labels.

When it comes to labeling content, labels are first defined according to entity and semantic labels, then content is labeled as various categories—first, second, and third levels. For example, a piece of content could be labeled as anime, Japanese anime, Naruto (a Japanese anime series), and Naruto Uzumaki (a main character of Naruto). Labels that are more detailed require the input of more resources and can grasp user needs more precisely.

Douyin also labels persons by analyzing the behavior of users based on their habits when using its app, then labels the users and optimizes the labels. In this process, the firm uses real-time machine algorithms. Labeled users with continuously optimized and upgraded labels are also called user portraits.

After that, the intelligent label-based recommendation comes into play. Through the A/B test, platform algorithms count newly labeled videos that users like and comment on, create new label portraits through continuous optimization, and match users with newly labeled similar videos. Thus, algorithm training is deepened to realize user-centered customized content.

China's large market has generated significant amounts of data. IDC statistics show that global big data storage volume reached 41ZB in 2019, and data generated in China accounted for about 23% of the global volume, ranking No.1 in the world. China's significant amount of data can improve the accuracy of algorithms and provide fertile ground to optimize Douyin algorithms. Companies with larger amounts of data provide training for algorithms that is more adequate. This helps companies drive all-round innovations in their products, attract more users, generate more data, and create a virtuous cycle.

Relying on big data and intelligent algorithms, Douyin accurately captures user portraits and grasps user needs to facilitate precise positioning and drive all-round innovation (Fig. 2.14). The firm applies innovations to products and services in its business ecosystem, and it uses real-time and extensive big data to build a flexible supply chain. Douyin promotes the development of new business models and ecosystems in the industry through short videos and live-streaming e-commerce, and drives innovations in exploring demand in consumer-related industries.

A digitalized economy provides consumers with new models of participation in product innovation. Digitalization helps companies better and more comprehensively understand consumers and allows consumers to express their needs in new ways, creating new models for consumer participation in technological innovation. Among the new models, consumer crowdfunding (a combination of group buying and pre-purchases to raise funds for a project online) is a mature and effective model for consumers to participate in technological innovation.

Under the crowdfunding model, companies could have direct contact with consumers to "connect innovation and consumers," providing unlimited possibilities for both entrepreneurs and consumers. As digitalization continues to advance,

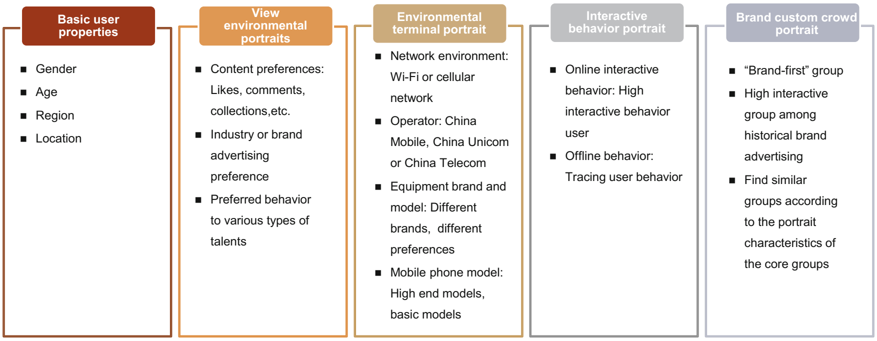

Fig. 2.14 Douyin captures user portraits and assesses user needs. *Source* Jusha Xueyuan, CICC Research

we believe that additional entrepreneurs will use the crowdfunding model to display their creative ideas and showcase their brands to consumers.

For example, data from china.com.cn shows that the Xiaomi Youpin crowdfunding platform launched 655 crowdfunding projects as of December 31, 2020. These crowdfunding projects had 2.74mn participants, and the highest number of participants of a crowdfunding project for a single product was about 176,000.[20] Through crowdfunding platforms, consumers support brands willing to innovate, promote innovations in products and consumption, and accelerate product innovations in consumer-related industries.

The rise of Generation Z consumers has created an opportunity for the growth of Xiaomi's crowdfunding platform. Xiaomi targets younger users, and it has sought to produce "the first mobile phone for young people" since it was founded. With the rise of Generation Z, young people's consumption behaviors have also changed, and they are more willing to try new methods of consumption. In recent years, Xiaomi's crowdfunding platform has launched products that are popular among Generation Z consumers, such as "the first mattress for young people" and "the first set of wooden furniture for young people."

2.3.2 Digital Economy Reduces the Cost of Consumer Participation in Technological Innovation

We divide the costs of technological innovation into four categories[21]: Design costs, communication costs, production costs, and payment and other transaction costs. Design costs include the labor cost of making product innovation plans and the

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[20] https://www.sohu.com/a/478813588_120287279 [Chinese only].

[21] Baldwin et al., (2011). Modeling a paradigm shift: From producer innovation to user and open collaborative innovation.

cost of completing product designs . Communication costs arise from communication between departments of a company and between companies because product innovation and R&D often involve cooperation between multiple departments of a company or even multiple companies. Production costs are needed to transform innovations into products or services. Payment and other transaction costs also exist in innovation. As China's per capita GDP is still low, it is difficult for consumers to pay to participate in technological innovation. Thus, the proportion of consumers participating in innovation in China is much lower than that in developed countries.

We believe that the development of the digital economy will change this situation, reduce the cost of consumer participation in innovation, and promote consumer participation in technological innovation. First, digitalized and modular production designs reduce design costs. Second, the popularity of open-source communities and development of the internet cuts communication costs. Third, the popularity of large-scale customized manufacturing lowers production costs for products and means that consumers participating in scientific and technological R&D only need to pay for R&D design, which helps scientific and technological innovators transform innovative designs into real products. Fourth, with the rise of internet-based financial services, various convenient payment methods such as Alipay and WeChat Pay have reduced payment costs. In particular, Alipay charges a transaction fee of 0.6–1%, substantially lower than overseas payment-service providers.

For example, in the US, non-card-issuing payment service providers such as Visa and MasterCard charge fees of 2–2.5%, and card-issuing payment service providers such as American Express charge fees of 3–3.5%. To summarize, we believe that the development of the digital economy will increase the proportion of Chinese consumers participating in innovation and facilitate the transition from the current corporate innovation model to the coexistence of three models (corporate innovation, independent consumer innovation, and open-source cooperation) in China's consumer-related industries.

Chapter 3
Digital Innovation

Abstract Innovation in digital industries is one of the key factors to building a country's competitiveness. With a focus on the semiconductor industry and the software industry, this chapter mainly analyzes the path of innovation of China's digital economy. Semiconductors are the cornerstone of the global information and communications technology (ICT) industry. The semiconductor industry has a global division of labor, with upstream and downstream players being interdependent and regional cooperation being indispensable. Although Chinese companies mainly focus on downstream intermediate products and end product assembly, we suggest China undertake a range of measures to promote innovation, especially those relating to semiconductor manufacturing. Software is also an important component of the digital economy. Currently, China's supply of system and high-end application software may not be sufficient, and China relies heavily on imports. This current situation may lead to security risks, including import suspension and data leaks, and also may result in a lack of long-term drivers for industrial upgrades. We believe the security risk of the software value chain is rooted in inadequate technological innovation, and it is important to catch up in innovation in both system and application software.

Regarding the path of innovation of China's semiconductor industry, we think China can step up efforts in innovation in the following two directions: More Moore's Law and More than Moore's Law. The former indicates that China can leverage existing mature technologies and follow the path of leading global companies. China can increase capex on mature process capacity and step up R&D on semiconductor equipment, materials, and electronic design automation (EDA) tools, aiming to eliminate the supply chain bottlenecks and improve the command of core technologies. More than Moore's Law, on the other hand, suggests that China can highlight catching up with global players more quickly in terms of advanced integrated circuit (IC) processes; deepen its presence in potentially disruptive technologies such as new semiconductor materials, new computing architectures, and chip integration; and increase investment in the wide band-gap semiconductor materials and advanced packaging markets, in which technology advancement is more visible and the gap between China and overseas economies is narrow.

CICC Research, CICC Global Institute, *The Rise of China's Innovation Economy*,
https://doi.org/10.1007/978-981-99-8231-8_3

There are four major driving forces behind innovation in the semiconductor industry. Industrial policies have played a crucial role in stimulating technological innovation and driving industrial development. Many countries and regions have unveiled a variety of incentive policies to bolster the semiconductor industry, mostly consisting of fiscal and taxation measures. In addition to industrial policies, capital, talent, and technology are three indispensable elements for the semiconductor innovation.

Regarding the path of innovation of China's software industry, system software and application software take different forms. System software innovation is an aggressive process led by scientific R&D. Setting standards for system software tends to create monopolies. It promotes innovation and requires long-term input of funds and resources. Innovation of application software happens gradually, and it is rooted in the constant feedback exchanges between users and developers. Small new entrants find it difficult to compete with the low pricing of large players, making application software an ideal target for venture capital.

Therefore, we believe that domestic software companies can innovate in the following ways. Almost all new-generation system software is open source, giving domestic companies a chance to participate in the setting of new standards. In fact, Chinese software developers are already an important part of the international open source community. We suggest that domestic companies increase independent innovation to keep up with global cutting-edge system software technology. In terms of application software, we think standardization is the key to success. Some companies in China are able to define local standards for application software, but only a few can set global standards. We believe opening up more application scenarios and clients is crucial for domestic companies to strengthen the competitiveness of their products.

3.1 Digital Industries in the Global Value Chain

Digital industries are experiencing deepening global division of labor, and their global value chains are becoming increasingly complex. We believe China is moving up along the semiconductor value chain to claim "innovation premium", but is facing risks, including suspension of oversea supply and data leaks in the software value chain. Technological innovation plays an important role in shaping the current status of China's digital industries. Innovation enables semiconductor companies to enjoy competitive strength, while insufficient innovation results in security risks in the software industry.

3.1.1 Semiconductor: Global Division of Labor and Cooperation Along the Global Value Chain

The global division of labor along the semiconductor value chain has become common practice with the emergence of economic globalization. China has seized the opportunity to become an important participant in the global semiconductor value chain. After experiencing a rapid growth stage driven by its large market size and abundant supply of engineers, China's semiconductor industry may transit to an innovation-driven growth stage.

3.1.1.1 Semiconductor Value Chain: The Global Division of Labor and Regional Interdependence

The semiconductor industry presents two major characteristics: Vertical and regional division of labor, and regional clusters.

There are two reasons behind the vertical division of labor. First, companies benefit from economies of scale by expanding production. With the advancement of manufacturing processes and the increase in silicon wafer size, the number of transistors on a chip has increased dramatically, and the yield has improved substantially. Therefore, capacity expansion can lower unit production cost, thereby enhancing competitiveness. Second, companies in the semiconductor industry must commit high levels of sunk cost. Expansion of wafer manufacturing capacity for advanced chips requires far more capital expenditure and R&D spending than before. Aside from some tech giants, most companies are unable to continue to move forward due to lack of sufficient funds.

The semiconductor industry is also undergoing regional division of labor, and each country or region plays a different role, some pivotal, along the value chain (Fig. 3.1). In design tools, three electronic design automation (EDA) tool companies (two in the US and one in Europe) have a combined global market share of 85%. In chip manufacturing, about 75% of production capacity is concentrated in East Asia (Japan, South Korea, the Chinese mainland, and the Taiwan region of China). In manufacturing equipment and materials, the US has a market share of more than 50% in at least five subdivided wafer fab equipment (WFE) markets. Japanese companies have high shares in the semiconductor materials market. European company ASML dominates the extreme ultra violet (EUV) lithography market. In end products markets, the US has a share of more than 90% of the high-end logic chips market.

Overall, while various sections of the semiconductor value chain are relatively scattered, there is a high degree of regional concentration within some of the sections. Therefore, in the event of *force majeure* such as earthquakes, flooding, and fire, the supply chain can be highly fragile.

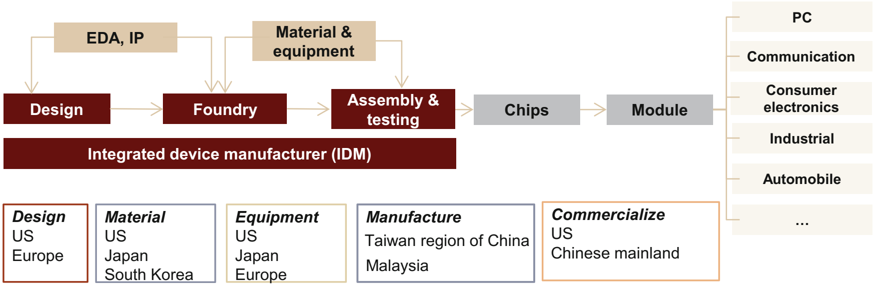

Fig. 3.1 Semiconductor value chain and global division of labor. *Source* SIA, BCG, CICC Research

3.1.1.2 The Innovation Premium Curve of the Semiconductor Value Chain: An Analysis on Premium from Competitive Strength

We construct an "innovation premium" chart to illustrate and analyze[1] the competitive landscape of the global semiconductor value chain based on the size of the global semiconductor market and industrial value chain, as well as the current positions and innovation capabilities of different countries and regions.

From a static perspective, the semiconductor value chain demonstrates a typical smile curve (Fig. 3.2). The value added in design, equipment, foundry, and packaging & testing is gradually decreasing, while the value added of integrated device manufacturer (IDM) is rising. Given different levels of strength in innovation, product premiums of different segments vary. The design process has high value added given its rapid technological advances and as it is an asset-light business model. The asset-heavy business models of the foundry and packaging & testing segments affect their margins. IDM enjoys high premiums given the high R&D spending and fixed-asset investments.

US companies are concentrated at the two ends of the smile curve, and Chinese companies are moving up the value chain to achieve "innovation premium". The heavy R&D investments in the design, equipment, and IDM segments help US companies maintain their innovation premium and leading positions. Companies from the Chinese mainland and the Taiwan region of China focus on the foundry, packaging, and testing businesses. In 2020, the Chinese mainland's R&D spending on foundry, packaging and testing was much higher than that of other countries and regions. In addition, high R&D spending on the design segment has brought about considerable returns for companies from the Chinese mainland.

From a dynamic perspective, innovation is an effective way for companies to maintain their competitive strength. By analyzing the changes in the "innovation premium" curve for 2000–2020, we have found that global IDMs have maintained

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[1] Y-axis is the average R&D expense ratio (measurement of innovation) and average gross margin (measurement of premium) of major countries and regions' key listed companies at each section of the semiconductor value chain. X-axis is all sections of the semiconductor value chain, including design, equipment, foundry, packaging and testing, and vertically integrated manufacturing.

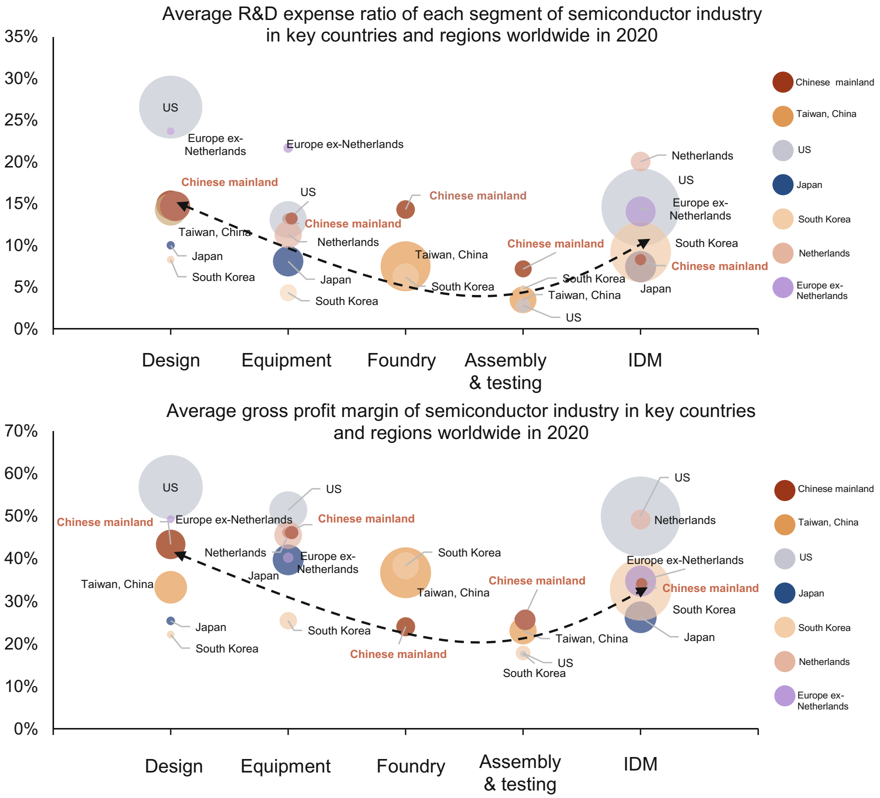

Fig. 3.2 The "innovation premium" curve of the global semiconductor value chain in 2020. *Note* Size of bubble refers to total revenue of respective country and region in the corresponding markets (based on CICC estimates). *Source* Wind, Bloomberg, IC Insights, Trendforce, Digitimes, China Semiconductor Industry Association, CICC Research

stable gross margins over the past two decades (Fig. 3.3). Fluctuating market demand and intensifying competition have posed a limited impact, mainly thanks to R&D expense ratio rising steadily by 0.25 pct annually. US IDMs maintained a gross margin of over 50% with an R&D expense ratio of 12–15%, while Korean IDMs maintained a gross margin of over 30% with an R&D expense ratio of 3–8%.

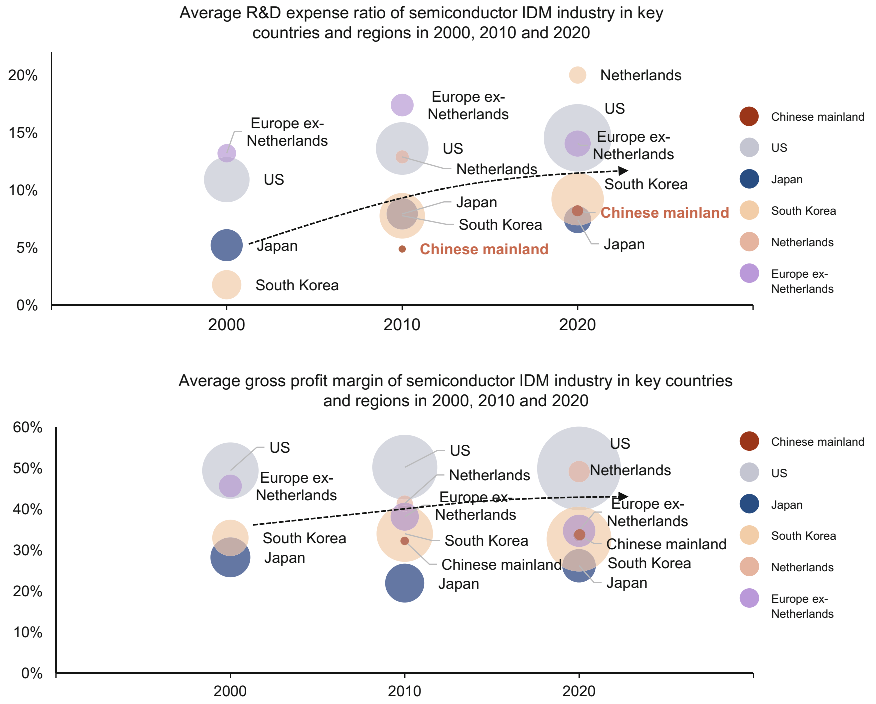

Fig. 3.3 The "Innovation premium" curve of the IDM industry of major countries and regions in 2000–2020. *Note* Size of bubble refers to total revenue of respective country and region in the corresponding markets (based on CICC estimates). *Source* Wind, Bloomberg, IC Insights, Trendforce, Digitimes, China Semiconductor Industry Association, CICC Research

3.1.2 Software: China is Facing Security Risks in the Global Value Chain

3.1.2.1 Insufficient Supply of Local Software

China's digitalization demand exceeds overall software supply. We believe local software supply is unlikely to suffice during the new round of digitization in China. IDC expects IT spending by Chinese enterprises to reach US$700bn in 2021, ranking No. 2 in the world, while Bloomberg and Gartner forecast China's software industry output value at US$439bn in 2021, revealing a significant supply gap. In contrast, the supply and demand for software is largely balanced in developed countries such as the US (Fig. 3.4).

China's software industry faces trade deficit. China's software export value has maintained steady growth since 2013, except for declines due to trade frictions or COVID-19. Export value reached US$191.5bn over January to May in 2021,

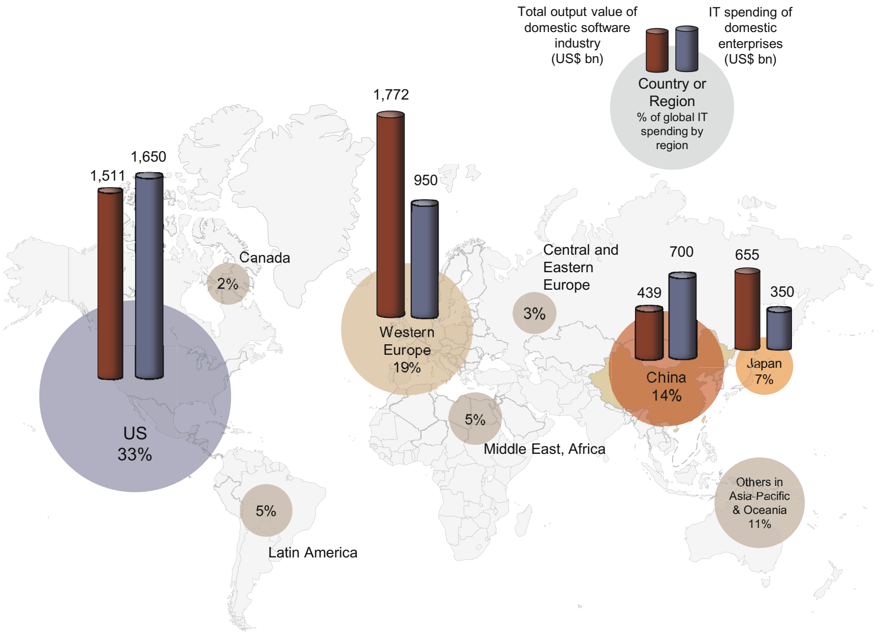

Fig. 3.4 Software industry output value and IT spending in major regions, by company (2021e). *Source* Bloomberg, IDC, Gartner, CICC Research

rising 15.4% YoY, and is around 3% higher than the same period in 2019.[2] Data from the National Bureau of Statistics (NBS) shows that China's import value of computers, software, and auxiliary equipment bottomed out at end-2015 before increasing sharply from 2017 onwards. Overall, we think the trade deficit still exists, but is gradually narrowing.

Supply shortage essentially lies in system software. We divide the software and services sector into three parts: System software (operating system, database, middleware, virtualization technology, and cybersecurity); application software (industrial software, management software, and industry application software); and IT services (IT consulting and implementation). By scale, the US is the largest market in all three major subsectors—especially in system software.

There are relatively large gaps in localization of different software subsectors in China. Chinese companies have developed competitive strength in the fields of enterprise resource planning (ERP), construction cost estimation, and healthcare IT, with the import substitution rate measured by the share of software demand met by domestic companies surpassing 50% (Fig. 3.5). However, the system software and industrial software segments are monopolized by overseas industry giants due to the R&D barriers to entry and the mainstream of industry standards set by foreign

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[2] Source: Ministry of Industry and Information Technology.

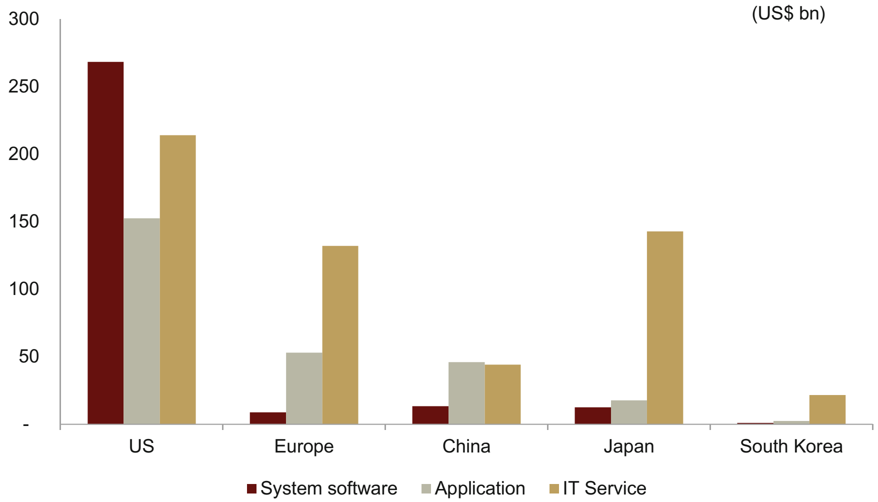

Fig. 3.5 Size of software and services subsectors in major regions. *Note* Based on data from select companies; aggregate revenue of the 2,712 companies we selected from Bloomberg's software and technological services sector; data as of end-July 2021. *Source* Bloomberg, CICC Research

companies, making breakthrough in system and industrial software a key focus of R&D in China.

In sum, there is visible supply gap in China's system and application software industry. Despite a high import substitution rate for some software subsectors, a large proportion of domestic demand for system and application software (e.g., industrial software and ERP) is dependent on imports (Fig. 3.6). We believe the technological innovation-driven enhancement of China's software technology is important for ensuring the security of the domestic software value chain.

3.1.2.2 Potential Security Risks in China's Software Value Chain

China's software supply chain faces the risk of suspended software authorization and services. The bulk of industrial design software (an important production tool) and system software (the foundation for the operation of application software) in China are imported from the US.

There are also concerns over data security. "Backdoor" in the context of software offers access to privileged information bypassing normal authentication. Software developers can modify or test bugs during the development process through a so-called "backdoor," which is a software vulnerability that may become an entry point for hackers However, if hackers manage to gain access to this backdoor, or developers fail to close it before the software hits the market, it would create risk of data leaks. This is an issue that has been gaining increasing attention across the globe.

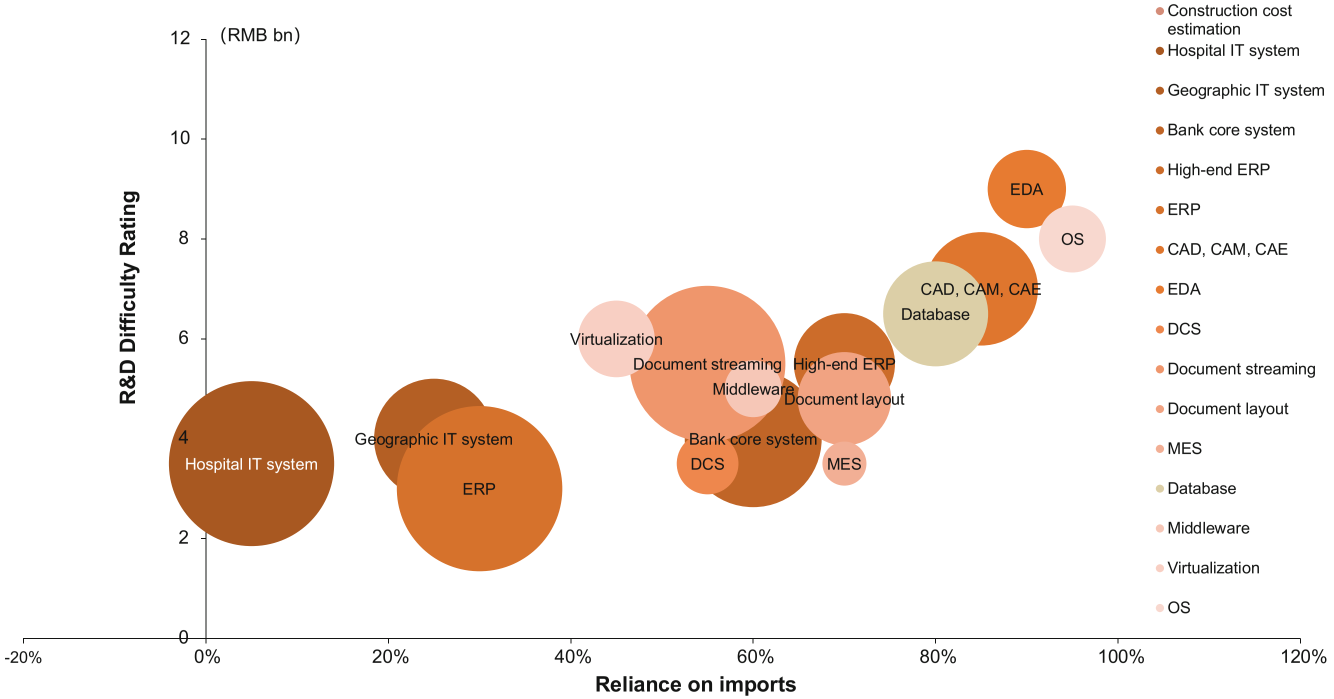

Fig. 3.6 Reliance on imports, by software subsector. *Note* Data as of end-December 2020; size of bubbles indicates the market size; reliance on imports = 1-import substitution rate. *Source* IDC, Qianzhan Industrial Research Institute, CCID, corporate filings, CICC Research

Software value chain risk is more worrying in the long term. The US restrictions on tech exports to China are now focused on hardware, mainly because the software shortage can be addressed with alternative solutions such as open source software. However, the software value chain risk will affect China's digitalization and industrial upgrade over the long term, in our view. The upgrading of software technology is a constant process globally, and contributing to this process is important for China's ability to narrow its gap with other countries in IT.

3.1.2.3 Software Value Chain Risk Rooted in China's Lagging Technological Innovation

Gross margin is a key measure of a product's competitiveness and a company's innovation capability. Software companies in China tend to have lower gross margins compared to their European and US counterparts, particularly in the system software sector (Fig. 3.7). High barriers to entry for system software also contribute to higher gross margins. In contrast, labor-intensive IT services tend to have lower gross margins. European and US software companies generally have higher gross margins than Asian companies.

R&D expenditure is a good indicator of a company's innovation efforts. US companies spend more on R&D for system and application software than Chinese companies (Fig. 3.7). Developing system and application software requires more intensive investment than labor-intensive IT services. The US is the top spender on R&D for system and application software, followed by China and Europe. China and South Korea have higher R&D spending on IT services than other countries.

Chinse software companies lag in system and application software. Global markets for system software (operating system and database) and industrial software (computer-aided design [CAD] and EDA) are both dominated by overseas companies, mostly from the US. Chinese software providers are less competitive even in local markets. We believe it is important for China to catch up in these fields, so as to guarantee the security of its software value chain.

Having analyzed China's position in the global value chain of the semiconductor and software industries, we believe it is crucial to enhance innovation inputs in the semiconductor industry to maintain advantages, and catch up in both system and application software to ensure security. In the following sections, we conduct in-depth analysis on the path of innovation in the semiconductor and software industries. Section 3.2 focuses on how to mobilize policy, capital, talent, and technology resources to promote semiconductor innovation. Section 3.3 provides a framework and targeted solutions for system and application software innovation.

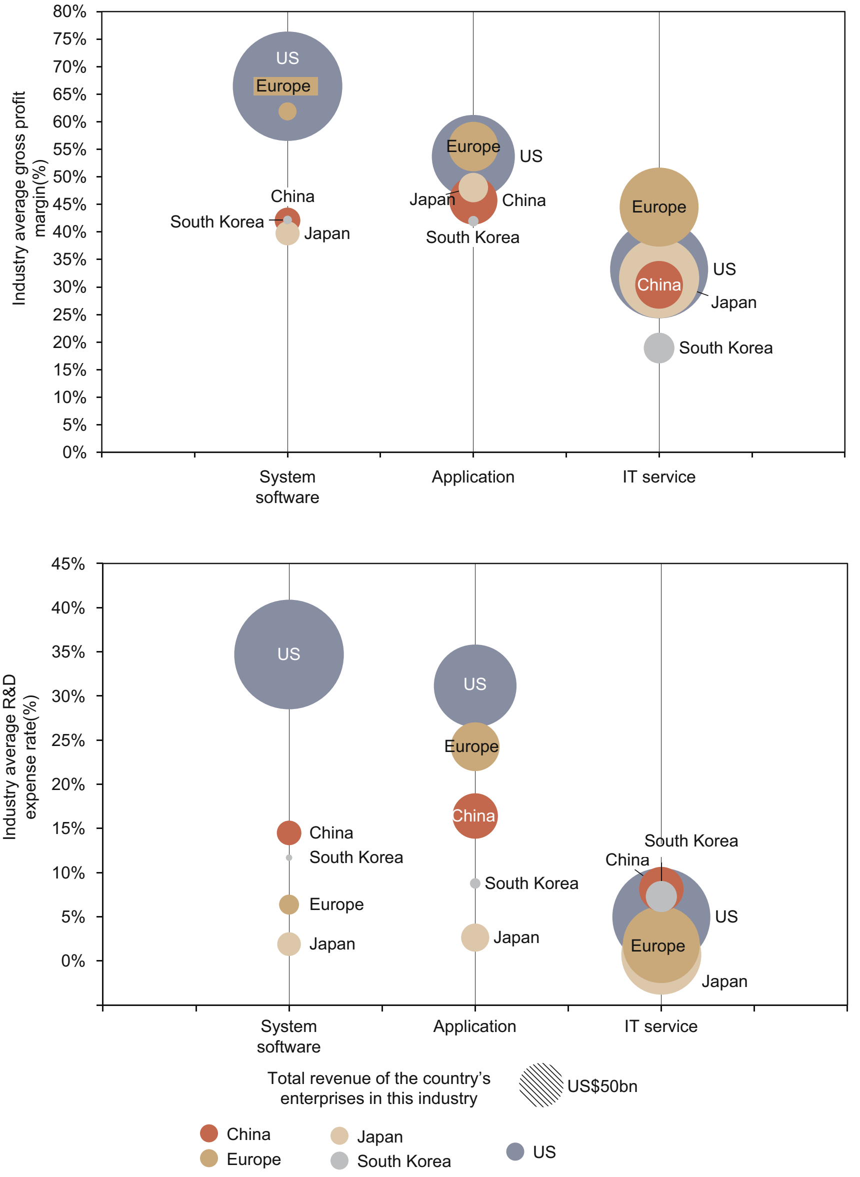

Fig. 3.7 Software innovation capability in terms of GM and R&D expense ratio. *Note* Based on data from select companies; we select 2,712 companies from Bloomberg's software and technological services sector; data as of July 2021. *Source* Bloomberg, CICC Research

3.2 The Path of Innovation in the Semiconductor Industry

3.2.1 The Dual Perspectives of Semiconductor Innovation

The Chinese mainland's market for semiconductors is large and focuses on downstream intermediate products and terminal product assembly. We suggest companies from the Chinese mainland step up efforts to develop technologies in areas where they are weak for now, and may continue to innovate to catch up with the global leading players.

Incremental innovation is the general principal driving the development of the semiconductor industry. However, it is undeniable that radical innovation has triggered leapfrog development of some technologies, and moderately ahead-of-the-curve innovation is also necessary. There are two main directions for China's semiconductor innovation. One is "More Moore's Law", referring to advanced processes of the entire value chain. The other is "More than Moore's Law", which is developing disruptive technologies in computing principles, materials, devices, computing architecture, and chip integration. This includes boosting investment in semiconductors with new structures and that are made with new materials and advanced packaging fields that have clearer outlook and narrower gap with overseas countries.

In the manufacturing field, China lags behind other countries and regions in advanced nodes and wafer manufacturing capacity. Although China can narrow the gap in wafer production capacity by increasing capital investment, it is unlikely to narrow the gap in the advanced processes in the short term since international competitors continue to innovate in this area. Due to the long development cycle, heavy capital investment, and winner-take-all characteristics in advanced nodes, an oligopoly is likely to be formed in the global market in some segments. Therefore, to narrow the gap with global top tier players, Chinese semiconductor companies can continue to develop wafer manufacturing equipment, materials, and EDA tools, along with sustaining investment in manufacturing capacity.

"More than Moore's Law" focuses on potential disruptive technologies in the semiconductor industry. It refers to technologies and products that are based upon or derived from circuit design and system algorithm optimization and the use of new materials rather than on simply adding more transistors to a chip. At present, the semiconductor process node has reached 5 nm (mass production). Foundries have started to work on the 3 nm node or below. However, advancing nodes alone cannot fully meet market demand for better chip performance and more complicated functions. We expect innovative technologies to drive further improvements in the semiconductor industry in the post-Moore era from the four aspects below:

The area of computing principles includes quantum computing, photon computing, and neuromorphic computing using quantum action law, photon action law, and neuromorphic information processing law to replace classic electronic computing and NOR characterization computing. In theory, these can be used with certain types of algorithms to increase computing efficiency.

As for materials and devices, compound semiconductors (e.g., GaAs, GaN, SiC, and Ga_2O_3) have advantages of wide bandgap, high thermal conductivity, and high radiation resistance. These semiconductors enjoy notable advantages over silicon-based (Si) semiconductors when used in high-speed, high-frequency, and high-power applications. Carbon-based devices (e.g., graphene and carbon nanotube) have the advantage of high electron migration rate and can theoretically work at a rate of nearly 200 times higher than that of silicon-based devices. Flexible devices (e.g., carbon nanotubes and ZnO) can theoretically be better adapted to applications in the field of flexible electronics. New types of memory (e.g., phase-change memory, ferroelectric RAM, magnetic core memory, and resistive random-access memory) have the advantages of high reliability, fast access speed, and low power consumption compared with traditional memory such as DRAM, NAND flash, and NOR flash.

Regarding computing architecture, RISC-V has the advantages of being open source and featuring simple architecture and modular design. RSIC-V is actively promoted in the Internet of Things (IoT) and other related fields. With the advances in AI technology (especially the emergence of compute unified device architecture [CUDA] technology), heterogeneous architectures have now become widely used. The integration of storage and computing (i.e., resistive random-access memory) combines the current two basic functional units of computer storage and computing into one unit. In theory, it can form a better coupling with AI algorithms (i.e., neural networks).

Regarding chip integration, advanced packaging technologies such as Chiplet, system in packaging (SiP), and 3D stacking are important trends for the packaging industry.

3.2.2 Industrial Policies Have Supported Semiconductor Innovations

Industrial policies have a profound impact on the semiconductor industry around the world. The majority of countries and regions involved in the semiconductor industry chain have actively supported the development of the semiconductor industry. Different industrial policies have been implemented at the different stages of the semiconductor industry, including the formation of industrial alliances; the creation of industrial clusters; and the promotion of industry-university-research integration, fiscal and tax incentives, direct investment, and support for technology transfer. Given the current stage of development and external environment of China's semiconductor industry, we believe the industrial policies of other countries and regions may offer some examples of successful cases for China.

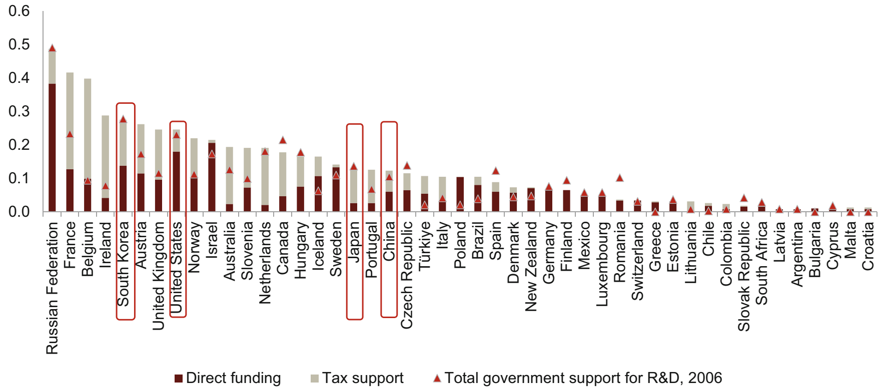

Fig. 3.8 Direct government funding and tax support for business R&D as a percentage of GDP by country and region (2006 vs. 2016). *Source* OECD, R&D Tax incentives database, CICC Research

Based on the formal incidence[3] of support measures and transfer mechanism,[4] the Organization for Economic Co-operation and Development (OECD) categorizes the support measures of governments around the world in the semiconductor value chain, and derives a two-dimensional matrix.[5] Using this matrix as a research framework, the OECD has found that government support for R&D is one of the most common forms of state intervention in the semiconductor value chain. Less common is for governments to intervene directly in the production of semiconductors, either through direct ownership of semiconductor companies or by exerting strong influence on the decisions of local companies.

Tax incentives are the most common support measure for global semiconductor industries. The OECD pointed out that R&D tax incentives have become an important way to increase the attractiveness of the national research ecosystem.[6] Russia, Israel, and the US rank as the top three in the world in terms of direct government funding for R&D as a percentage of GDP, and France, Belgium, and Ireland rank as the top three in terms of tax support for business R&D as a percentage of GDP (Fig. 3.8).

Government support mainly comes from the fiscal budget. The OECD's analysis results for 21 large companies operating across the semiconductor value chain indicate that total global government support has exceeded US$50bn over 2014–2018.

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[3] Formal incidence refers to whom or what a transfer is first made, enabling distinctions to be made between support measures that target output levels (i.e., enterprise income), unit returns, intermediate inputs, knowledge (e.g., R&D and IP), or other value-adding factors that are either variable (e.g., labor) or quasi-fixed (e.g., capital and land).

[4] Transfer mechanisms describe how a transfer is generated, whether through a direct cash transfer; tax or other revenue foregone by the government; transfers induced by regulations or price controls; or the assumption by the government of risks that would otherwise be borne by the private sector.

[5] OECD, (2019). Measuring distortions in international markets: The semiconductor value chain.

[6] OECD, (2019). Measuring distortions in international markets: The semiconductor value chain.

This comprises support provided through government budgets, and below-market borrowings and equity investment.

Budgetary support mainly targets R&D, capex, and revenue. Most budgetary support targets R&D of semiconductor vendors. This is consistent with the trend of the semiconductor industry needing a large amount of R&D investment. Governments also provide fiscal support for capex of companies that involve asset-heavy operations, such as Taiwan Semiconductor Manufacturing Co (TSMC), Vanguard International Semiconductor Con (VIS), and other wafer foundries. In addition to targeted subsidies for R&D and capex, governments also support enterprises by reducing or exempting corporate income tax.

3.2.3 Three Drivers Behind China's Semiconductor Innovation

The semiconductor industry emphasizes innovation in R&D, technology iteration, and business model. There are three key drivers behind: Capital, talent, and technology.

3.2.3.1 Capital: Chinese Companies Narrowing the Gap with US Companies in R&D Expense Ratio, But Still Lag Behind in Terms of Total R&D Spending

Average R&D expense ratio of Chinese companies has risen from 5% in 2010 to about 10% in 2020, versus over 15% for the US companies during this period (Fig. 3.9). Meanwhile, China's total R&D spending on electronics and electrical equipment, technology hardware, software, and computers was lower than that of the US in 2015–2020 (Fig. 3.10).

Industry funds can play a role in guiding the semiconductor industry. Investment in the semiconductor industry can be classified into four categories. Investing in

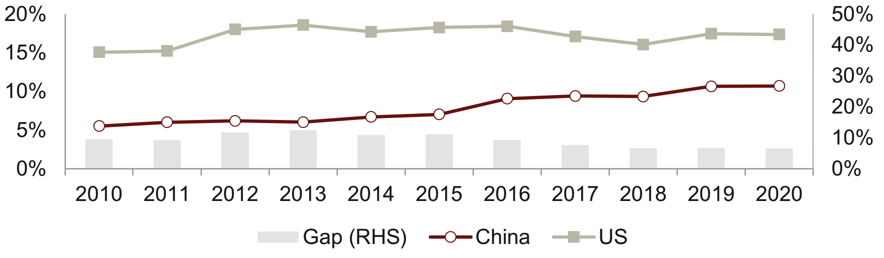
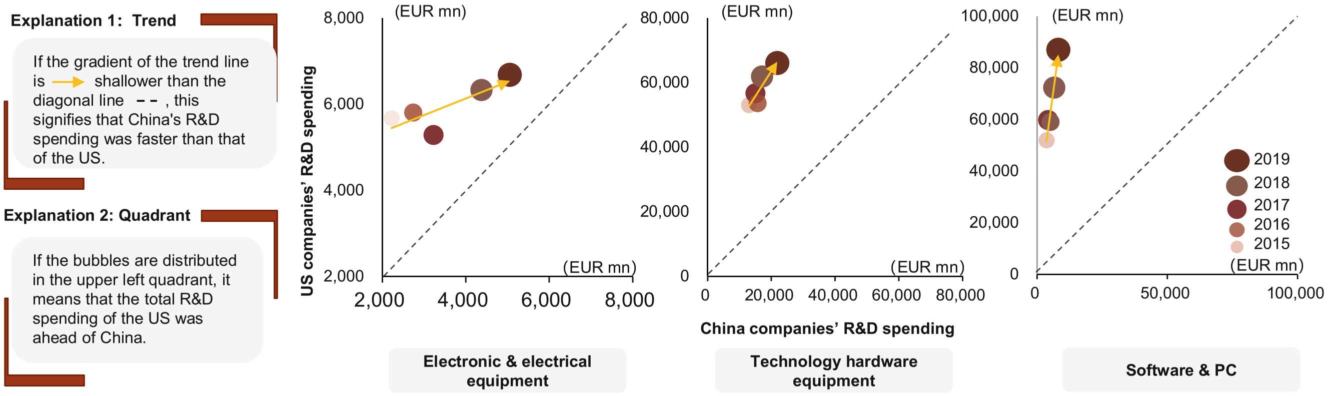


Fig. 3.9 The gap in the average R&D expense ratio of listed semiconductor companies between China and the US is narrowing. *Source* Wind Info, Bloomberg, CICC Research


Explanation 1: Trend

If the gradient of the trend line is → shallower than the diagonal line - - , this signifies that China's R&D spending was faster than that of the US.

Explanation 2: Quadrant

If the bubbles are distributed in the upper left quadrant, it means that the total R&D spending of the US was ahead of China.

Fig. 3.10 China saw faster growth in R&D spending in electronics and electrical equipment than the US, but R&D spending on technology hardware and software and growth were slower than those in the US in 2015–2020. *Source* The EU Industrial R&D Investment Scoreboard, CICC Research mature products has low barriers to entry and low risks, while investing in projects in their incubation stages has high barriers to entry and high risks. Investing in industrial clusters requires large and continued investments in infrastructure, which has high barriers to entry and high risks, but can bring high long-term investment returns and indirect improvement to the regional economy and supporting industries. In addition, investing in basic science has limited direct capital returns in the short term, but it contributes to the development of the upstream stages of the semiconductor industry. However, basic science is a necessary but not sufficient condition for enhancing the competitiveness of the semiconductor industry.

Reasonable division of labor between public and private capital can improve the effectiveness of investment. The central government can coordinate planning of local governments to form the optimum industrial structure and provide guidance in talent education and basic science. Local governments can formulate plans based on the existing regional conditions. Public capital should invest based on market-oriented practices as a market participant. Private sector should avoid repeated and blind investment.

3.2.3.2 Talent: Quality and Structure of Expertise Could Be Improved Despite the High Number of Professionals in China

China's semiconductor industry has more employees than that of the US, but Chinese expertise focuses more on design than on manufacturing at the current stage. Compared with the US and other countries and regions with mature semiconductor industries, China has a larger number of employees in the IC industry, and the industry is growing faster. As of end-2019, the number of people directly engaged in the IC industry in China was about 512,000, a YoY increase of 11.04%, of which the total number of people in the design and manufacturing industry was 353,000, versus 277,000 in the US.[7] In 2019, the number of employees in China's semiconductor design industry and manufacturing industry was 181,200 and 171,900, versus 92,000 and 185,000 in the US.[8]

The attractiveness of the domestic semiconductor industry still could be improved. In 2019, only 13% of China's college graduates majoring in semiconductors entered the semiconductor industry, and this figure was 55% for the 28 universities that have exemplary microelectronics colleges.

Upside potential in the number of foreign employees in China's semiconductor industry. US citizens accounted for just 59% of senior employees in the US semiconductor industry in 2012–2016, with the remainder mainly from India, China, South Korea, and other countries (Fig. 3.11). In 2020, Chinese citizens accounted for 87%

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[7] Source: China Center for Information Industry Development, White Paper on Talents on China's IC Industry 2019–2020, 2020.

[8] Source: China Center for Information Industry Development, White Paper on Talents on China's IC Industry 2019–2020, 2020.

of senior employees in listed semiconductor companies on China's STAR Market, and the US citizens accounted for 9% (Fig. 3.12).

China has a larger number of highly educated professionals in the semiconductor design and manufacturing fields than the US, but still has room for improvement in terms of the international ranking of corresponding universities. Some 39% of employees in the semiconductor design industry have master's degrees or above in China, and 43% have bachelor's degrees, both higher proportions than in the US. Among semiconductor manufacturing employees, 32% have bachelor's degrees and 20% have master's degrees or above in China, versus 19% and 8% in the US (Fig. 3.13). According to the QS World University Rankings 2021, 26 of the top 100 universities in electronics are in the US and eight are in China. Based on the 2019 Academic Ranking of World Universities (ARWU) released by ShanghaiRanking Consultancy, eight of the world's top 10 semiconductor-related universities are in the US (Fig. 3.14).

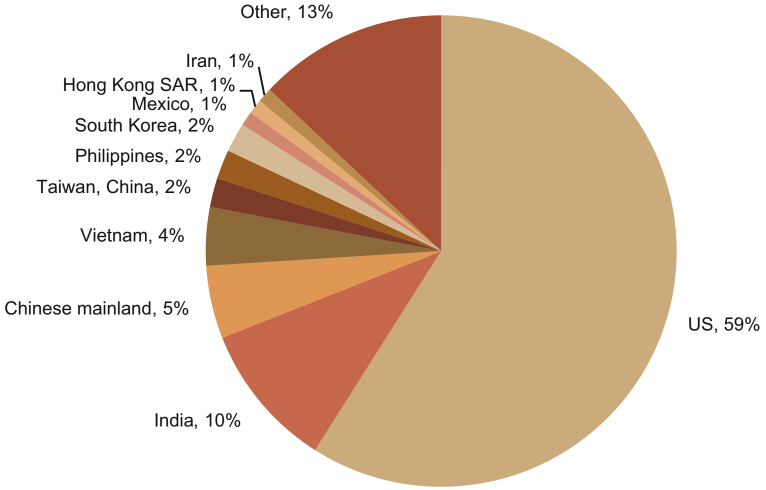
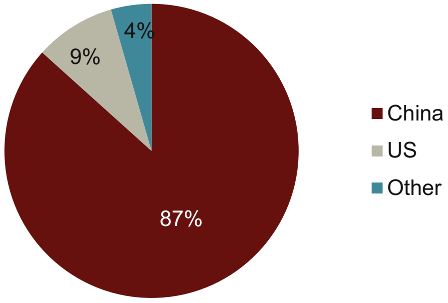


Fig. 3.11 Number of high-skilled workers in the U.S. "electronic components and products" industry by place of origin, 2012–2016. *Source* CSET, CICC Research

Fig. 3.12 Nationality of directors and senior executives of Chinese semiconductor companies listed on the STAR Market in 2020. *Source* Wind, CICC Research



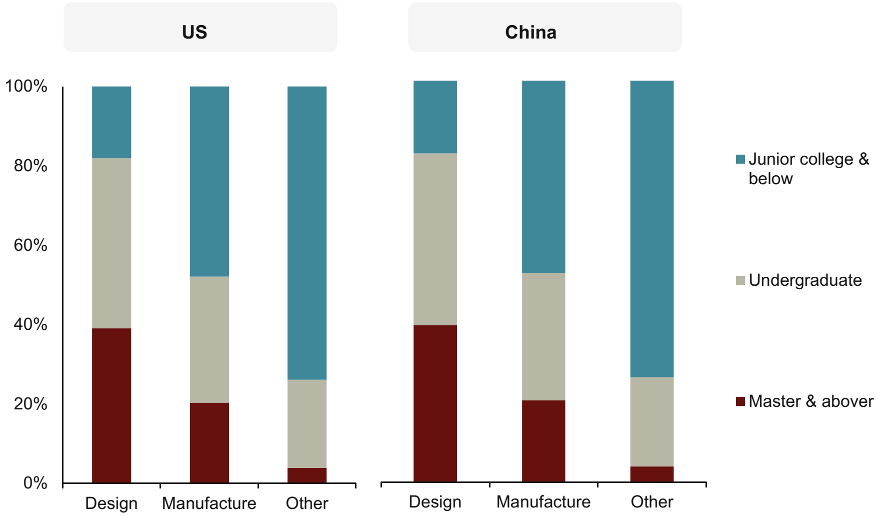
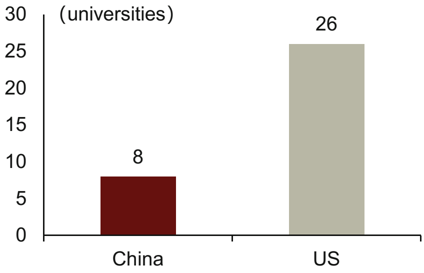


Fig. 3.13 Highly educated professionals account for a larger proportion in China's semiconductor design and manufacturing industries than the US in 2019. *Source* Wind, ACS 2019, CSET, CICC Research

Fig. 3.14 Number of Chinese and the US universities ranked among the world's top 100 in electronics by QS Consultancy (2021). *Source* QS, CICC Research



In addition, US professionals are more experienced than their counterparts in China. Most employees are aged between 35 and 50 in the US, and 25–35 in China. It takes time for Chinese professionals to accumulate experience. We suggest that China pay more attention to foster senior professionals and create a sound environment for innovation and entrepreneurship.

3.2.3.3 Technology: China's Academic Research is Gaining Momentum; International Cooperation is Deepening

China's academic research in the field of semiconductors has achieved positive initial results; number of papers rising steadily in recent years. Compared with the US, EU, and other developed countries and regions, China is a newcomer in academic

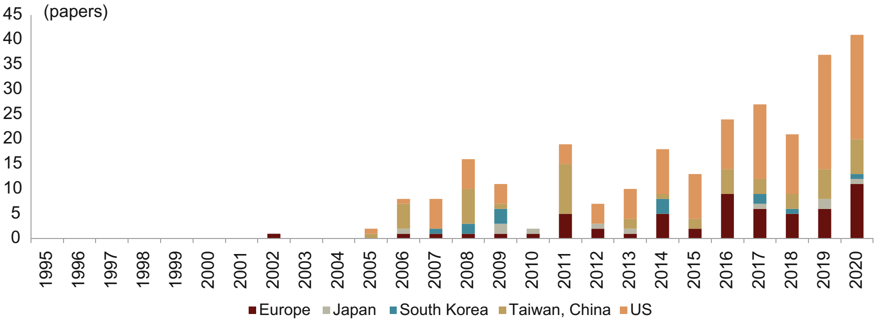


Fig. 3.15 Number of China's papers on semiconductor in cooperation with other countries and regions. *Note* Data comes from IEDM, ISSCC and VLSI. *Source* Stiftung Neue Verantwortung, CICC Research

research in semiconductors, and it is lagging far behind in terms of the number and quality of papers produced. However, the number of papers in which Chinese authors have participated has steadily increased thanks to supportive policies and rising investment.

Number of papers in cooperation with other countries and regions continues to grow. SNV data shows that number of papers jointly published by authors based in the US, EU, and China rose YoY from 1995 to 2020 (Fig. 3.15). In addition, the proportion of jointly-published papers has remained high. At present, Chinese scholars mainly cooperate with scholars in the US and EU. International cooperation has become an important feature of academic research in the semiconductor industry. Moreover, the number of PCT patent applications in the semiconductor field in China continued to increase from 2000 to 2020, especially after the launch of the STAR Market in 2019.

3.3 Solutions to Innovation of System Software and Application Software

3.3.1 Innovation Schemes in the Software Sector

Software innovation can be both vigorous (e.g., unsolved problems and brand-new platforms) and gradual (demand-based upgrades) in terms of the innovation model. The major incentive for the innovation of system software lies in the high pricing secured by monopolies. For example, companies such as Microsoft and Oracle enjoy high profit margins thanks to their monopolies. In markets for IT services and application software, however, new entrants can take market share from their predecessors by offering value-for-money products. Thus, it is important for frontrunners to leverage low pricing that they secured through economies of scale to disadvantage small rivals. Unlike the innovation in system software and new IT architectures that originates from R&D at universities and large software companies, innovation in application software and IT services relies more on feedback and actual user needs.

In terms of commercialization, users can acquire either open or closed source system software at a much lower cost than if they develop the software themselves. Commercially, IP and monopoly guarantees profitability of closed-source software, while open source software is more about the commercialization of public knowledge. We believe that the performance and anecdotal reputation of products and the quality and stability of services are important factors affecting the profitability of application software and IT services.

System software innovation is vigorous, and uncertainty exists over the length of the R&D period and the potential of market size. Prices for such software must be minimized to maximize social benefits. Hence, developing system software—closed or open source—requires extensive and sustained investment. Innovation of application software, however, happens gradually, and it is driven by market demand, making application software a better choice for venture capital. Investment in software projects from which returns do not match the risk needs more policy and funding support from the government (Fig. 3.16).

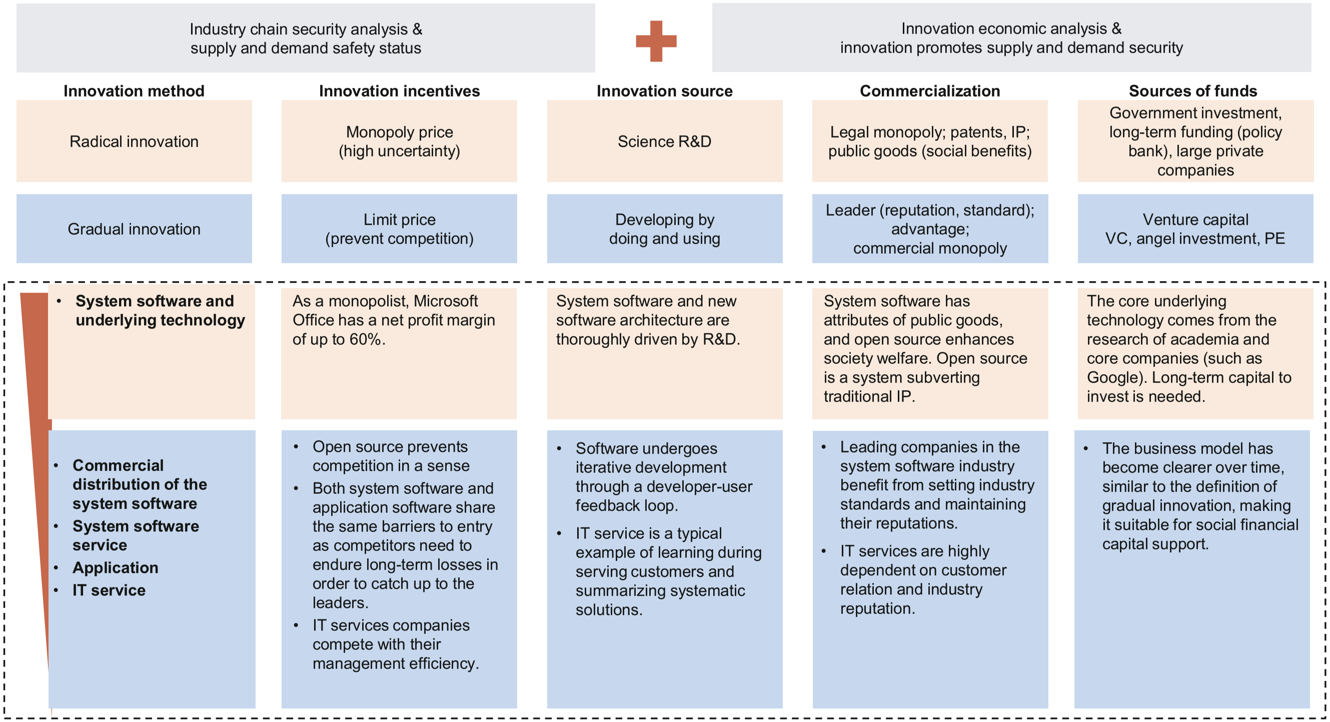
Innovation of system software and application software can be achieved in following ways. For system software, we believe open source technology provides a reasonable solution to system software innovation. Given developed countries' first-mover advantage in system software, we think it is difficult for China to adhere to a closed-source roadmap and start from scratch. The global adoption of open source technology offers domestic system software companies an opportunity to catch up with their foreign counterparts. For application software, we believe that participation in the setting of industry standards is a decisive factor for market position in the application software sector. Chinese companies are excluded from setting standards for industrial design software such as CAD, CAE, and EDA; therefore, we believe the setting of standards will be a major focus of China's application software innovation in the future.

3.3.2 System Software Innovation: Embracing Open Source

3.3.2.1 Open Source Technology: A Hindrance or a Boost to Software Innovation?

Is open source technology a hindrance or a boost to the software innovation? The open source community offers a platform for developers around the world to develop software projects jointly. However, free open source software may squeeze the profit at commercial software companies, and discourage them from continuing to invest in software R&D.

Open source is good for innovation. Figure 3.17 presents the pros and cons of open source software, according to research by Bitzer and Schroder in 2005. Bitzer



Industry chain security analysis & supply and demand safety status

Innovation economic analysis & innovation promotes supply and demand security

Innovation method	Innovation incentives	Innovation source	Commercialization	Sources of funds
Radical innovation	Monopoly price (high uncertainty)	Science R&D	Legal monopoly; patents, IP; public goods (social benefits)	Government investment, long-term funding (policy bank), large private companies
Gradual innovation	Limit price (prevent competition)	Developing by doing and using	Leader (reputation, standard); advantage; commercial monopoly	Venture capital VC, angel investment, PE
• **System software and underlying technology**	As a monopolist, Microsoft Office has a net profit margin of up to 60%.	System software and new software architecture are thoroughly driven by R&D.	System software has attributes of public goods, and open source enhances society welfare. Open source is a system subverting traditional IP.	The core underlying technology comes from the research of academia and core companies (such as Google). Long-term capital to invest is needed.
• **Commercial distribution of the system software** • **System software service** • **Application** • **IT service**	• Open source prevents competition in a sense • Both system software and application software share the same barriers to entry as competitors need to endure long-term losses in order to catch up to the leaders. • IT services companies compete with their management efficiency.	• Software undergoes iterative development through a developer-user feedback loop. • IT service is a typical example of learning during serving customers and summarizing systematic solutions.	• Leading companies in the system software industry benefit from setting industry standards and maintaining their reputations. • IT services are highly dependent on customer relation and industry reputation.	• The business model has become clearer over time, similar to the definition of gradual innovation, making it suitable for social financial capital support.

Fig. 3.16 Innovation models in the software industry. *Source* CICC Research

Advantages

- Leveraging massive developer collaboration
- Knowledge spillover brings social value
- Stronger incentives for developers
- Borderless cooperation
- User-developer effect
- Disciplined branches bring healthy competition and elimination
- "A small boat turns around easily" will not be trapped in a development dead end

Disadvantages

- Redundant development
- Decentralizing the research and development efforts of the community
- The high degree of code reuse makes it impossible to trace the source

Fig. 3.17 Pros and cons of open source software. *Source* Bitzer & Schroder (2005), CICC Research

and Schroder[9] concluded that innovation of open source software costs less than that of closed source software, and that the market shift from monopoly to competition can enhance the technological strength of developers of both open source and closed source software.

Open source is applicable to software sector because of economies of scale. Marginal cost of data reproduction is almost negligible for software companies, meaning that increases in cost are limited when service to a new user starts. In addition, the software industry features non-competitive supply. The cost of replicating and transmitting data is almost zero, and data use by new users does not raise supply cost for software companies.

Which type of software can better adapt to the open source model? Open source is not an ideal option for application software. Despite the advantages listed above, open source software has its shortfalls. Most open source software is system software for IT maintenance, operating systems, and databases. Open source software is normally less competitive in terms of user interface (UI), product documentation, and usability tests. In addition, it often cannot satisfy business demand for recovery of work and high availability (a measure of software performance). The root cause is that open source software is made for and developed by users, and a large proportion of participants in the open source community are IT administrators. Hence, free open source application software is generally less user friendly than paid open source-based software or commercial closed source software.

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[9] Bitzer, J., Schroder, P. (2005). The impact of entry and competition by open source software on innovation activity[R]. Working Paper 2005–12, Aarhus School of Business.

International competition of open source community. Open source has an impact on international competition and supply chain security as well. Technically, the open source community are not bound by national borders, but developers are. This can lead to potential value chain security risks related to code management platforms, foundations, and licenses. The trend towards open sourcing of system software is already well established globally. To safeguard value chain security, it is important for China to encourage domestic developers to join this trend and establish a leading role in the global open source community. Github predicted that China will have the world's most active open source developer communities by 2030.

However, currently, China's role in the global open source community is extensive but not necessarily influential. To increase influence, it is important for Chinese companies to participate more in significant open source projects and donate more open source projects to the global community. If domestic developers are unable to exert influence on the global community, it is likely that China's own open source community will attract fewer developers.

3.3.2.2 Open Source Technology is a Feasible Solution to China's System Software Innovation

Open source software has become an important infrastructure for new-generation software. Open source software is released under a license whereby the copyright holder grants users the rights to use, study, change, and distribute the software and its source code. The sharing of source codes can help prevent repetitive code development. Open source is a revolutionary trend increasingly used in the software industry. Open source system software such as Linux (operating system), Java (middleware), and PostgreSQL (database) is becoming mainstream, and upgrades and innovations are proceeding significantly faster than are those of closed-source software. Surveys by Gartner and Sonatype[10] show that 99% of global organizations are using open source software, and that 3,000 companies surveyed download open source software an average of 5,000 times per year.

Chinese system software developers are embracing open source ecosystem. US tech giants such as Google, Amazon, and Intel are taking part in developing open source projects and acquiring open source software companies. Meanwhile, Chinese software developers are also an important part of the international open source community, and multiple sources have been gradually opened since 2019, such as Huawei-led distributed database GaussDB, Linux distribution version of openEuler, terminal operating system framework OpenHarmony, and Alibaba-led cloud native relational database PolarDB and distributed relational database Oceanbase. Data from the China Academy of Information and Communications Technology shows that Alibaba had opened 2,172 sources as of September 2020, and Tencent and

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[10] https://jaxenter.com/sonatype-open-source-survey-shows-growing-importance-for-enterprises-104271.html.

Huawei had both opened more than 150 sources, including Apache projects such as Dubbo and CarbonData (Fig. 3.18).

Open source is extending to more industries and fields. Open source technology is being promoted in industries other than the internet industry. Goldman Sachs open sourced its data-modeling program Alloy; petroleum giant ExxonMobil released the Standards Devkit development kit to the open source community to create a standard data interchange format in the oil and gas industry; leading retailer Walmart made its OneOps platform for cloud and application lifecycle management available to other retailers. The open source trend is extending to various industries and fields.

Swiftness in open source upgrades have become a major competitive advantage for system software. The open source community saves programmers the repetitive work of developing the same codes that are already available in the community, which contributes to faster code upgrades. The collaboration and sharing in the open source community can also attract additional software developers, which in turn improves the user experience. This makes it possible to realize the concept of "open source ecosystem by and for developers".

Open source technology is likely to help Chinese software companies catch up with global frontrunners. The open source community creates a level playing field for global developers to access existing source codes and contribute their own codes. A growing number of domestic companies have been enhancing their influence in the open source community in recent years, and so have Chinese software developers.

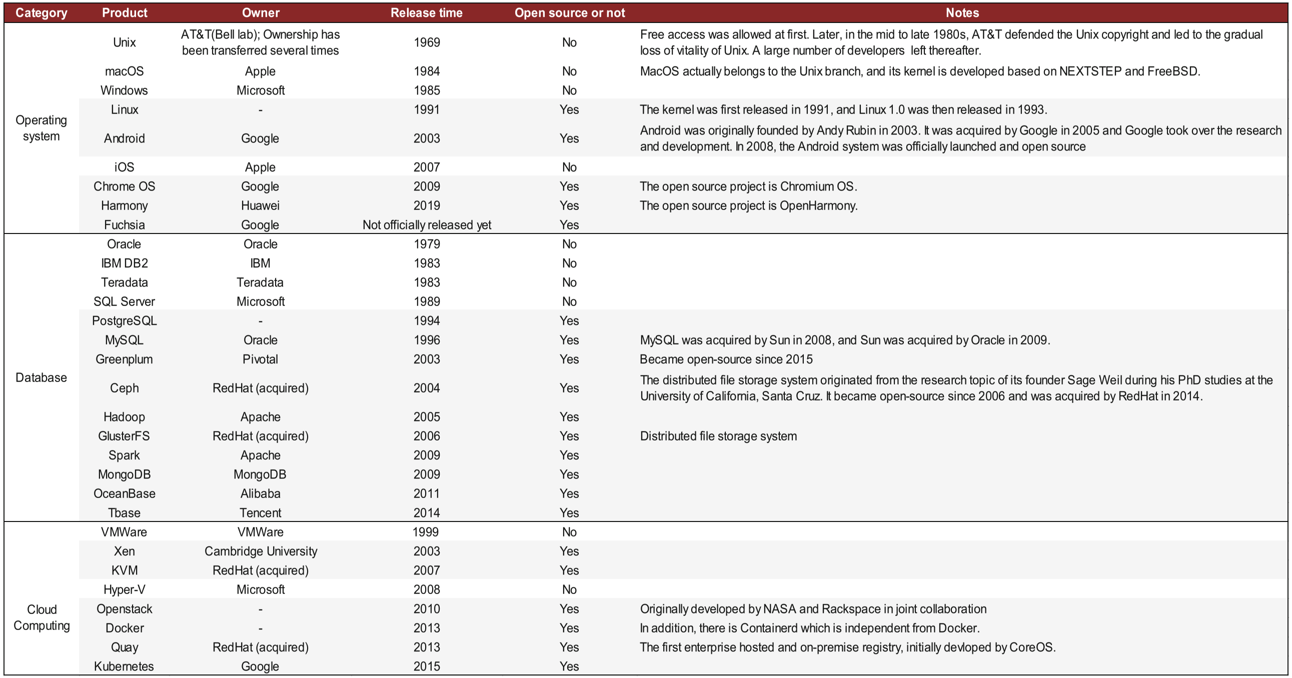
Therefore, open sourcing is a possible solution to system software innovation. We believe that Chinese software companies can base their research and innovation on the existing open source framework, and develop their own user-friendly system software. The bulk of existing domestic system software is based on open source software—e.g., Linux, Java, PostgreSQL, Hadoop, and Spark.

3.3.3 Application Software Innovation: From Follower to Standard Setter

3.3.3.1 Standards in Economics and How It Relates to Innovation

To examine application software innovation from the perspective of standard economics, we first distinguish formal standards from *de facto* standards. Economists classify standards into formal or *de jure* and *de facto* standards. Formal standards are based on deliberations of standards-writing organizations or mandatory standards issued by governments, while *de facto* standards are set by interest groups comprising single or a few enterprises, and are widely accepted by the market.

Looking into standards in the software sector, formal standards in software sector mainly apply to coding, such as the international UTF-8 standard and China's GB-2312 standard, while standards for application software are mainly launched by



Category	Product	Owner	Release time	Open source or not	Notes
Operating system	Unix	AT&T(Bell lab); Ownership has been transferred several times	1969	No	Free access was allowed at first. Later, in the mid to late 1980s, AT&T defended the Unix copyright and led to the gradual loss of vitality of Unix. A large number of developers left thereafter.
	macOS	Apple	1984	No	MacOS actually belongs to the Unix branch, and its kernel is developed based on NEXTSTEP and FreeBSD.
	Windows	Microsoft	1985	No	
	Linux	-	1991	Yes	The kernel was first released in 1991, and Linux 1.0 was then released in 1993.
	Android	Google	2003	Yes	Android was originally founded by Andy Rubin in 2003. It was acquired by Google in 2005 and Google took over the research and development. In 2008, the Android system was officially launched and open source
	iOS	Apple	2007	No	
	Chrome OS	Google	2009	Yes	The open source project is Chromium OS.
	Harmony	Huawei	2019	Yes	The open source project is OpenHarmony.
	Fuchsia	Google	Not officially released yet	Yes	
Database	Oracle	Oracle	1979	No	
	IBM DB2	IBM	1983	No	
	Teradata	Teradata	1983	No	
	SQL Server	Microsoft	1989	No	
	PostgreSQL	-	1994	Yes	
	MySQL	Oracle	1996	Yes	MySQL was acquired by Sun in 2008, and Sun was acquired by Oracle in 2009.
	Greenplum	Pivotal	2003	Yes	Became open-source since 2015
	Ceph	RedHat (acquired)	2004	Yes	The distributed file storage system originated from the research topic of its founder Sage Weil during his PhD studies at the University of California, Santa Cruz. It became open-source since 2006 and was acquired by RedHat in 2014.
	Hadoop	Apache	2005	Yes	
	GlusterFS	RedHat (acquired)	2006	Yes	Distributed file storage system
	Spark	Apache	2009	Yes	
	MongoDB	MongoDB	2009	Yes	
	OceanBase	Alibaba	2011	Yes	
	Tbase	Tencent	2014	Yes	
Cloud Computing	VMWare	VMWare	1999	No	
	Xen	Cambridge University	2003	Yes	
	KVM	RedHat (acquired)	2007	Yes	
	Hyper-V	Microsoft	2008	No	
	Openstack	-	2010	Yes	Originally developed by NASA and Rackspace in joint collaboration
	Docker	-	2013	Yes	In addition, there is Containerd which is independent from Docker.
	Quay	RedHat (acquired)	2013	Yes	The first enterprise hosted and on-premise registry, initially devloped by CoreOS.
	Kubernetes	Google	2015	Yes	

Fig. 3.18 Global new-generation system software mainly open source; now being rapidly promoted in China. *Source* Company websites, CICC Research

companies and are gradually accepted in the industry. Unlike system software, application software is used in specific downstream fields, and can itself be seen as a means of production. For application software companies, setting standards in niche markets can secure absolute advantage. Standards in the traditional industrial age are more about quality, while standards in the IT era focus more on compatibility and interfaces. In IT related sectors such as software, frontrunners that lead the setting of *de facto* standards usually have solid competitive advantages.

Software standards also have network externality. The format of application software files is a typical computability standard, e.g. Microsoft's Document, Excel, and PowerPoint and Adobe's PDF. Leading companies can establish first-mover advantage by being the first to set the *de facto* standards, to which late entrants would have to adapt.

The goal of standardization is to enhance efficiency and promote innovation. During the course of technological innovation, standards can also serve as a fair and open technology infrastructure, and a foundation for innovation-driven growth.

Monopoly over standard setting and network externality may impede innovation. A few software companies might leverage the network externality of standards to create solid competitive advantage for themselves. Leading companies may continue to monopolize the setting of industry standards, which in some circumstances would impede innovation (Fig. 3.19).

Standards should be properly governed to ensure their positive impact on innovation. In order to weaken the monopoly over standard setting, the common solution is to establish governance organizations to constrain standard setters and properly manage the standards. In the application software sector, the PDF Association and Open Document Architecture (ODA) are typical independent standard governance organizations, and their members are mainly industry participants other than standard setters Adobe and Autodesk.

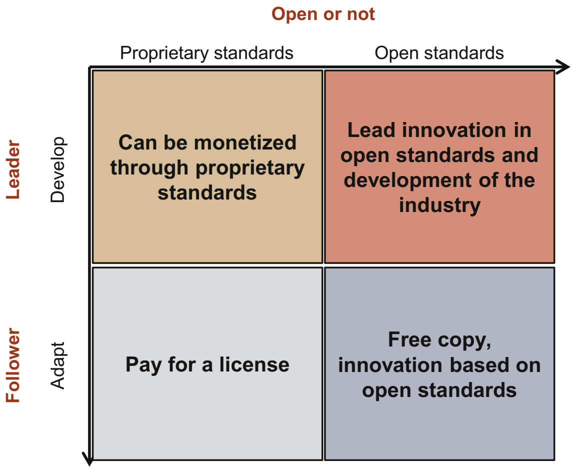


Fig. 3.19 Standard setters typically possess a more advantageous position in the market. *Source* David P A, Greenstein S, *The economics of compatibility standards: An introduction to recent research*, 1990, CICC Research

In addition, participation in setting industry standards is crucial for the security of the application-software value chain. Standards for the application software sector are set by leading providers along the value chain, a market position achieved by: Attracting large numbers of software developers by creating a comprehensive tool chain; making better use of existing programs and source codes; educating users via promotion among colleges and training agencies; recruiting distributors around the world to better service clients; and creating ongoing exchanges between developers and users (Fig. 3.20).

Therefore, Chinese application software companies can participate in the governance of international standards. By joining international standard governance organizations, Chinese companies can exert greater influence in setting new technological standards. As one of the most important application software markets, China can be an important participant in improving the standard governance network. We believe that by joining the global market, Chinese companies can help diversify technology and product standards and advance global innovation.

We suggest that Chinese companies start by setting local standards in emerging sectors. Domestic companies can set local standards for application software, but it is difficult for these standards to compete with existing international *de facto* standards. Thus, we believe Chinese companies can start by setting local standards in emerging sectors such as AI, Internet of Things (IoT), and industrial internet. We expect domestic software companies to lead the setting of standards for these emerging sectors.

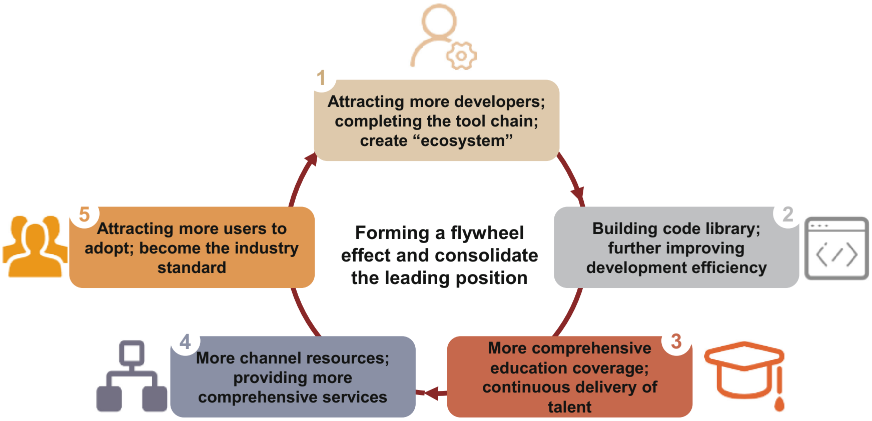


Fig. 3.20 Application software: importance of participating in the setting of industry standards. *Source* CICC Research

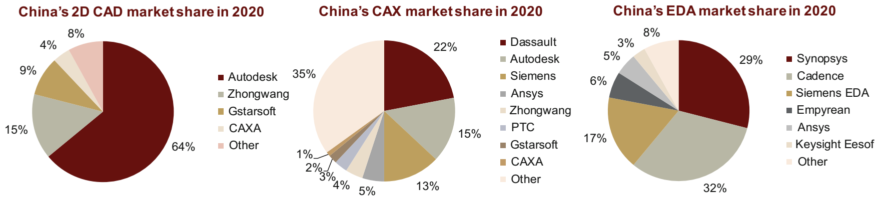


Fig. 3.21 China's market for industrial design software. *Source* e-works, CIMData, CCID Consulting, CICC Research

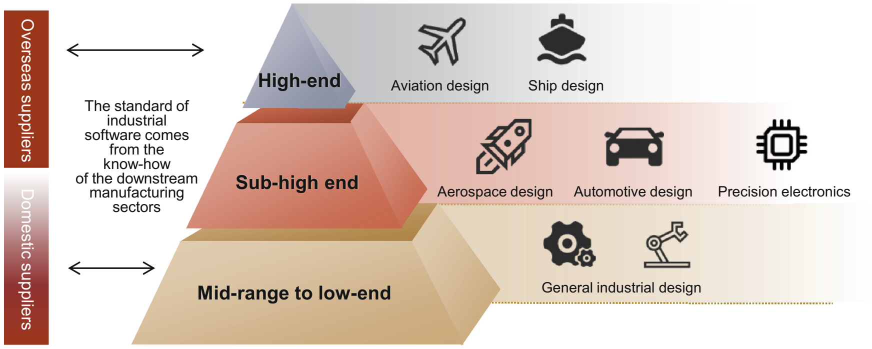
3.3.3.2 Standard Setting in China's Application Software Industry

In terms of industrial software, companies in China are currently unable to participate in standard setting. Industrial software standards are based on software companies' knowledge of downstream manufacturing technology. Industrial software needs to be continuously improved and adapt to special requests from clients in various industries. Overseas high-end manufacturing giants (e.g., traditional aviation, automotive, machinery manufacturing, and chips) have collaborated with foreign industrial software suppliers, leaving Chinese companies little chance to serve high-end manufacturers and participate in setting standards.

In comparison, overseas companies have absolute advantage in high-end industrial software and simulation software. The high-end industrial design and simulation software market (e.g., aviation design) in China remains dominated by foreign industry giants, while domestic industrial software is mainly used for low-end industrial design (Fig. 3.21). China is also relatively short of user-friendly simulation software, and is, therefore, susceptible to potential value chain risks.

Support from downstream sector is needed for Chinese industrial software companies to thrive over the long term (Fig. 3.22). Industrial software products cannot be improved without support from downstream manufacturing sectors. Besides enhancing their competitive strengths, more and more domestic high-end manufacturers began have started to adopt industrial software provided by domestic companies such as ZWSOFT and Empyrean. Nevertheless, we believe that the rise of China's industrial software will take some time; it might be 5–10 years until Chinese industrial software companies participate in setting international standards. During the course of achieving this, support from downstream sectors is essential for domestic industrial software suppliers to make breakthroughs in innovation and to narrow the gap with their foreign peers.

Management software and vertical market software, however, are two rare domains in which domestic players are capable of setting standards. Local standards for management process and vertical market software are well-established in China, and Chinese companies have naturally developed their own sets of standards for business management processes with Chinese characteristics, with many clients requiring heavy customization and intensive services. We see no significant supply chain risk in this sector.



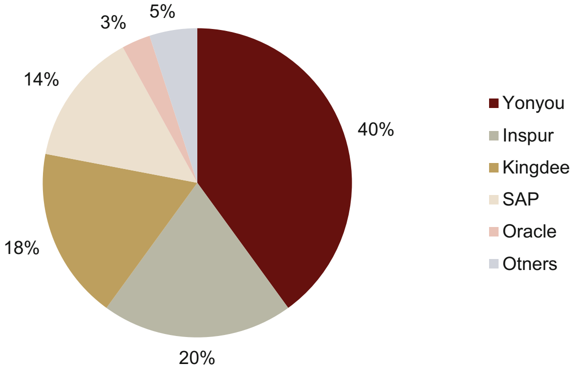
The booming domestic high-end manufacturing industry and the increase in the awareness of adopting domestic software products will further enhance the competency of domestic industrial software companies

Fig. 3.22 Support from downstream sector needed for Chinese industrial software companies to thrive over the long term. *Source* CICC Research

Setting local standards lays foundation for local market leadership. As extensive services are needed for vertical market software, local providers can respond more swiftly and offer prices that are more appealing than overseas providers. The domestic market for vertical market software is dominated by domestic companies (Figs. 3.23 and 3.24). However, this situation adds to the difficulties that Chinese companies have in going global. European and US enterprises had an early start in digital management, and some still dominate the high-end management software market. We believe domestic companies can begin their global expansion by tapping into developing countries.

After nearly 30 years of development, some Chinese companies can participate in the setting of global standards for office software. We see limited supply chain risk in this sector. For example, Chinese company KingSoft has developed its own WPS Office software, which is compatible with domestic operating systems, and it started

Fig. 3.23 China's ERP software market (2020). *Source* Qianzhan Industrial Research Institute, CICC Research



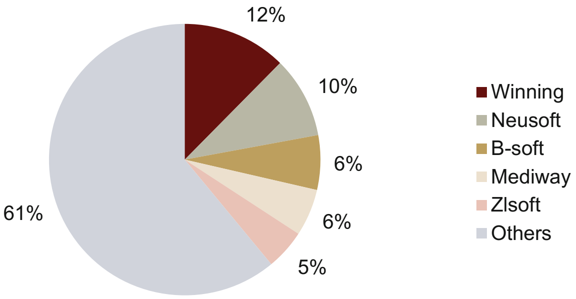


Fig. 3.24 China's hospital management system market (2020). *Source* IDC, CICC Research

deployment in mobile and cloud technology three years earlier than Microsoft. As of June 2021, MAU of WPS Office PC and mobile versions exceeded 199 and 296 mn.[11]

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[11] https://www.chinastarmarket.cn/detail/820759 [Chinese only].

Chapter 4
Engineering Green Transformation

Abstract We believe that the essence of technological innovation in the field of green energy lies in cost competition—i.e., the race to reduce the "green premium," which is the additional cost of choosing an emissions-free or low-emission innovation over an existing fossil-fuel-based option. The fossil fuel era was marked by high reliance on resource consumption amid increasingly scarce resources that constantly push up the marginal cost of energy exploitation. Thus, the purpose of technological innovation was to capitalize fully on limited fossil fuel resources. In contrast, green energies such as photovoltaic (PV) and wind do not face such constraints, but rather depend upon the manufacturing of equipment that has higher energy conversion efficiencies. We believe that more efficient and lower-cost energy equipment manufacturing is at the core of energy security. Specifically, the incentive for green energy improvement is that innovators gain greater market share and erect barriers to entry by leveraging lower manufacturing costs. However, the excess profits gained through cost reduction are not sustainable over the long term, as new entrants tend to acquire late-mover advantages.

In retrospect, we note that incremental innovation has become the dominant trend in the green energy sector, supplemented by radical innovation. Radical technological innovation in green energy creates a new generation of products, as evidenced by the improved efficiency and performance of PV and electric vehicle (EV) batteries. However, as the up-front cost can be high, companies try to gain cost advantages and leading market share via incremental innovations such as import substitution and lower unit consumption of raw materials. Internet of Energy (IoE) technology has spawned innovation in business models, and facilitated the integration of elements across the entire green energy industrial value chain on the back of digital transformation and smart technologies, which we believe will generate economic benefits and empower green energy development.

Through continuous technological innovation, the PV and EV battery technologies of domestic manufacturers are now on par with their foreign counterparts. This, coupled with strong cost advantages, enables Chinese manufacturers to capture a

CICC Research, CICC Global Institute, *The Rise of China's Innovation Economy*,
https://doi.org/10.1007/978-981-99-8231-8_4

larger share of the global PV and EV battery supply chain, with top-tier companies reaping excess profits. In addition, IoE and energy digitalization have created an incremental market and provided external incentives for infrastructure operators. We note that innovation is primarily driven by R&D, technological convergence, and business model transformation. Government finances, policy banks, capital markets, corporate funds, and venture capital (VC) and private equity (PE) institutions comprise the major sources of funding that support innovation in the green energy sector.

Governments play a pivotal role in cultivating demand through subsidies, guiding the upgrading of demand, and establishing demonstration projects, and we think that this will facilitate technological advances in the green energy industry. We also believe that this will provide a platform to test large-scale production and cost reduction. Fierce competition among enterprises has gradually forced quantitative change to culminate, whereupon qualitative change ensues. We think that the current favorable policies will be extended to a wider range of green energy development programs such as hydrogen energy, energy storage, and carbon capture technology. Given that China still lags developed countries in radical innovation, we expect the government to further improve its talent pool and R&D system, strengthen intellectual property rights (IPR) protection, and regulate the disorderly expansion of production capacity.

The major "horizontal risk" to China's green energy industry chain, stemming from the disruptive impact of new-generation technologies on existing ones, lies in the radical innovation of new battery technologies. We believe that the overall risk is manageable, as there is no obvious R&D gap between Chinese companies and their overseas rivals. The "vertical risks" that exist within the green energy supply chain for a particular generation of technology mainly arise from scarce resources and from equipment requiring import substitution. We think that the overall risk is manageable, given: (1) The gaps in the manufacturing of other equipment and supplies of raw material versus foreign counterparts are small; and (2) the shortage of key resources can be partially addressed by leveraging new battery technologies such as sodium-ion batteries. China also boasts a complete PV and automotive battery industrial value chain that ensures stable supply and demand.

4.1 Green Premium: The Essence of Technological Innovation in Renewable Energy

The essence of technological innovation in renewable energy is to reduce the green premium. In our report *Economics of Carbon Neutrality: Macro and Sector Analysis Under New Constraints*, we define the green premium as the percentage increase in the production cost of zero-emission technology versus current emission-generating technology. Since the beginning of the 21st century, there have been efforts to reduce the green premium in the energy development process. These efforts do not aim to create new demand and new products, but instead aim to encourage cost competition for particular forms of end-use energy (e.g., electricity) and reduce the cost of energy production and consumption This trend is manifested in a gradual shift to higher efficiency and lower costs in the use of energy, such as from wood to coal, then to petroleum and natural gas, and finally to photovoltaic and wind power. This chapter discusses the essence of technological innovation in green energy—cost competition; i.e., the race to reduce the green premium (Fig. 4.1).

Green energy innovation is less resource-dependent, with a growing focus on the manufacturing of energy conversion equipment. The fossil fuel era was marked by high reliance on resource consumption amid increasingly scarce resources that constantly push up the marginal cost of energy exploitation. Thus, the purpose of technological innovation was to capitalize fully on limited fossil fuel resources. In contrast, green energies such as PV and wind come from inexhaustible solar and wind energy and do not face such constraints, but rather depend upon the manufacturing of equipment that has higher levels of energy conversion efficiency. We believe that the more efficient and lower-cost energy equipment manufacturing is the core of energy security.

Against the backdrop of a global move towards carbon neutrality, green energy firms have focused on cutting the green premium to compete against fossil fuel firms. In our report *Economics of Carbon Neutrality: Macro and Sector Analysis Under New Constraints*, we estimated that the green premium in the carbon neutrality case is 6% for power generation and 36× for grid absorption compared with the base case. Thus, the overall green premium in the power sector would have been 17% in 2021 (assuming electricity transmission and distribution costs remain unchanged). Compared to the base case, power generation currently has a green premium of negative 17% in the carbon neutrality case, and will be negative 4% in 2030 (Fig. 4.2).

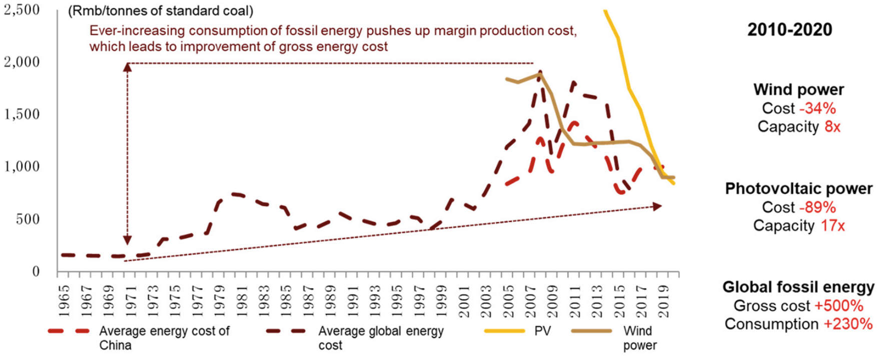


Fig. 4.1 Costs of fossil energy, wind power, and photovoltaic power. *Source* BP, Solarzoom, corporate filings of wind and solar power companies, CICC Research

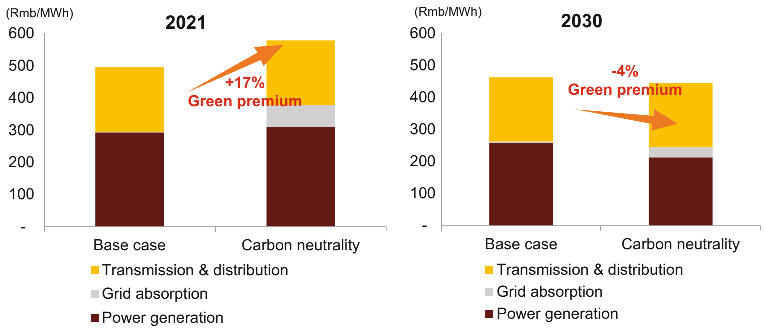


Fig. 4.2 Green premium in the power industry (2021 and 2030). *Note* The CICC alternative energy and electrical equipment team expects China's power system to achieve carbon neutrality in 2051. *Source* China Electricity Council, corporate filings of wind, solar, hydro, and nuclear power companies, GGII, L.E.K. Consulting, National Energy Administration, CICC Research

Technological innovation in green energy involves continuous reduction in green premiums. Specifically, the incentive for green energy improvement is that innovators gain greater market share and erect barriers to entry by leveraging lower manufacturing costs. However, the excess profits gained through cost reduction are not sustainable over the long term, which demonstrates the rapid upgrading of technological innovations. We note that incremental innovation has become the dominant trend in the green energy sector, supplemented by radical innovation.

Incremental innovation has played a dominant role throughout the history of development of green energy technology. Incremental innovations such as changes in silicon wafer dicing techniques and the replacement of conventional aluminum back-surface field (Al-BSF) solar cells with passivated emitter and rear contact (PERC) solar cells primarily depend on the optimization of manufacturing techniques and processes through practical learning. Radical innovation, in contrast, leverages R&D to produce new generations of products such as thin-film solar cells, perovskite solar cells, ternary lithium-ion batteries, and solid-state automotive batteries.

We think that innovation in the green energy industry is primarily driven by excess returns on R&D investment and market share gains. Governments, policy banks, capital markets, corporate funds, and VC and PE institutions are the major sources of funding for the green energy sector.

4.2 Green Energy Technology: Incremental Innovation as the Dominant Approach, Supplemented by Radical Innovation

4.2.1 Types of Innovation

Overall, radical innovation in green energy technology creates new generations of products, while incremental innovation involves progressive, small improvements that add value to existing products. Radical innovations are the foundation on which new products are built, with improvements in efficiency and performance to meet the changes or upgrades in demand. However, as the up-front costs are high, green energy companies seek to gain cost advantages on the back of economies of scale and incremental innovations.

4.2.1.1 Radical Innovation in Green Energy

For the PV sector, radical innovation entails changes in the underlying light-absorption materials. The goal of technological innovation in the PV sector is to enhance the cost advantages of PV power generation over other energy sources. Radical innovation in PV technologies mainly entails changes in the underlying light-absorption materials, whose properties (bandwidth) determine the upper limits of theoretical photoelectric conversion efficiency and production cost.

For the EV battery sector, radical innovation means bringing about higher-energy-density, safer, and lower cost products. We note the two radical innovations in EV batteries. First, since 2010, the demand for lithium-ion batteries has shifted from consumer electronics to electric vehicles, with the latter placing more-stringent requirements on energy density, safety, and the cost. This has driven the upgrade of lithium-ion battery technologies from liquid-state lithium cobalt oxide ($LiCoO_2$) cathodes to liquid-state lithium iron phosphate (LFP) and ternary cathode materials. Second, we think that third-generation battery technologies, as represented by solid-state batteries, will bring about higher-energy-density, safer, and lower cost products. We expect mass production to commence around 2030.

4.2.1.2 Incremental Innovation in Green Energy

Green energy companies try to gain cost advantages and to lead market share through incremental innovation, which entails small improvements and upgrading of new-generation technologies, such as through import substitution, lower unit consumption of raw materials, and enhancement of material efficiency.

For the PV sector, the development of mainstream crystalline silicon PV cells is driven by incremental innovations. Over the past 15 years, we have seen three major advancements in this sector. First, the shift towards domestic production of polysilicon and breakthroughs in cold hydrogenation technology significantly lowered the energy consumption of polysilicon production. Second, breakthroughs in diamond wire cutting technology for monocrystalline silicon (mono-Si) wafer production facilitated the replacement of polysilicon wafers with high-efficiency mono-Si wafers. Third, the replacement of Al-BSF solar cells with high-performance PERC solar cells led to a 94% decline in solar energy cost per kWh and a 10% increase in cell efficiency.

For the EV batteries sector, incremental innovation and economies of scale have driven down costs. Incremental innovation is embodied by two main areas. The first one is a trend towards a rising portion of domestically produced core products. For example, the proportion of domestically produced core manufacturing equipment for lithium-ion batteries rose to 90% in 2020 from 20% in 2008. The domestic production rate of lithium-ion batteries and relevant materials increased to 100% in 2015 versus 40% in 2010. The second one is lower unit consumption of raw materials due to the increasing energy density of batteries. For example, through technological upgrades that improve compaction density, LFP batteries have increased their energy density from 110–120 Wh/kg to 200 Wh/kg. The energy density of ternary lithium-ion batteries climbed to 300 Wh/kg from 160 Wh/kg thanks to increased nickel content resulting from material optimization (Figs. 4.3 and 4.4).

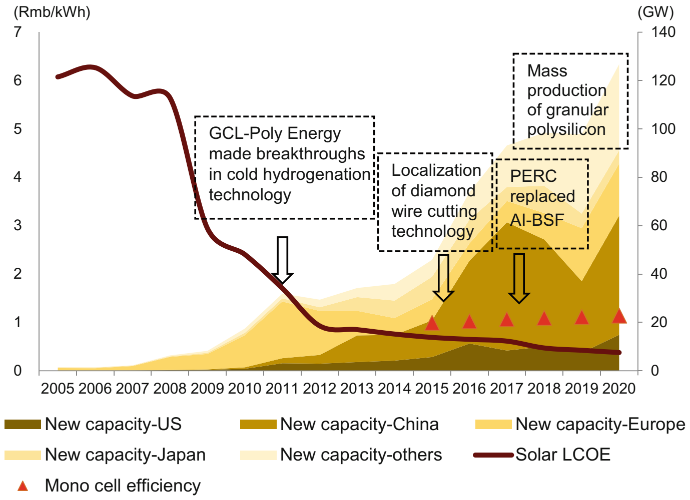


Fig. 4.3 Incremental innovation in PV cells. *Source* BP, CPIA, CICC Research

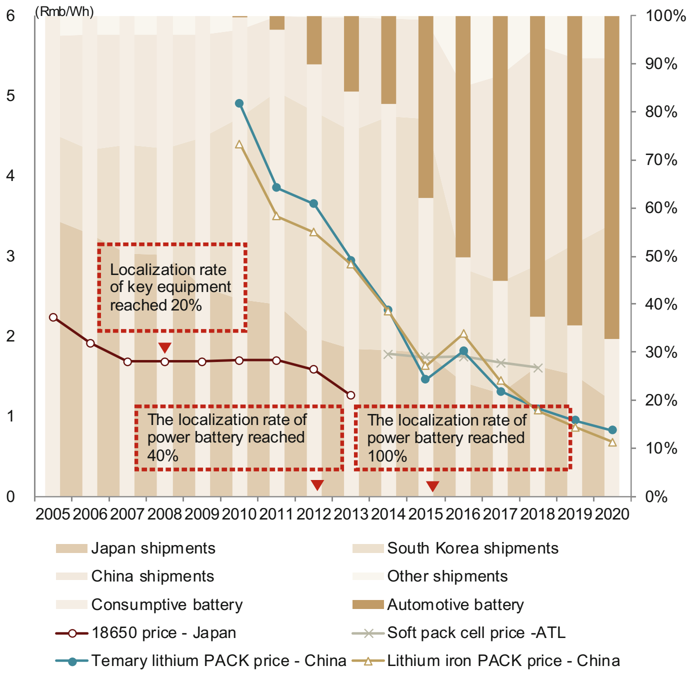


Fig. 4.4 Incremental innovation in EV batteries. *Source* GGII, CIAPS, CICC Research

4.2.1.3 Innovation in Green Energy Business Model

With the development of information technology, the traditional energy industry is facing challenges from green transformation and digital transformation. IoE integrates electricity infrastructure and various forms of energy production and consumption with advanced information and communications technologies (ICT) and internet technologies to achieve intelligent management of multiple energy sources. IoE technology enables the reconstruction of existing energy production and sales systems and the integration of elements across the entire green energy industrial value chain on the back of digital transformation and smart manufacturing, which we believe could generate economic benefits and empower green energy development.

IoE and energy digitalization are in essence innovative technologies that improve the production, transmission, and consumption of traditional energy products. The heart of IoE lies in the integration and reorganization of existing internet technologies, the traditional power grid, and infrastructure for various energy forms (e.g., electricity, gas, heat). Moreover, IoE and energy digitalization involve service innovation. Digitalization could empower traditional power grids, reshape traditional energy service models, and spawn new business formats. It could also improve customer experience, enrich sources of income, and further facilitate the development of IoE.

4.2.2 Incentives for Technological Innovation

There are several methods to stimulate green energy innovation, including introducing new products and new technologies and cutting product prices to gain more market share and impede the entry of new competitors. Opening up incremental markets and employing external incentives also help.

4.2.2.1 Cost Reduction and Price Cut to Gain Market Share

The first way to stimulate green energy innovation is to introduce new products and new technologies. For example, over 2010–2020, the PV sector saw multiple rounds of technological innovation significantly drive down the levelized cost of energy (LCOE) for solar by 84% to Rmb0.38/kWh, making PV solar energy a promising substitute for traditional energy resources. GCL-Poly Energy employed cold hydrogenation technology to cut the cost of polysilicon production. Longi lowered the cost of wafer cutting by switching from traditional slurry-based wire sawing to diamond wire cutting technology.

We note that incremental technological innovation in the PV sector is continuously cutting costs, increasing product competitiveness, and enhancing the price advantage of PV over other energy sources for electricity generation. Throughout the cost cutting process, we note that the government provides support to PV manufacturers by: (1) Offering subsidies to improve the internal rate of return (IRR) of PV projects, to boost downstream demand, and to alleviate the demand shock caused by antidumping and countervailing duties against Chinese-made solar products; and (2) launching the Top Runner plot project to accelerate the commercialization and application of technological innovations, and to facilitate industrial upgrading as well as the advancement of PV power generation technologies.

We take a closer look at technological innovation and cost reduction in specific segments. For example, the replacement of traditional Al-BSF solar cells with PERC solar cells could boost cell efficiency and reduce per-watt cost, making PERC solar cells a good substitute for Al-BSF solar cells (Figs. 4.5 and 4.6).

As EVs are consumer goods, the overarching goal of innovation in EV battery technology is to meet the consumer demand for longer-range, safer EVs. Cost reduction is at the core of market competition when there is no obvious technology gap among battery manufacturers. Over 2010–2020, Chinese manufacturers caught up with their foreign counterparts in automotive battery technologies through radical and incremental innovations. Overall, there is no obvious technology gap between Chinese companies and their overseas rivals.

The Ministry of Industry and Information Technology (MIIT) issued a “white list” of batteries approved for use in EVs that were eligible for subsidies. This stimulated demand in the domestic lithium-ion battery industry chain and brought about economies of scale. Domestic battery manufacturers along the industry chain have

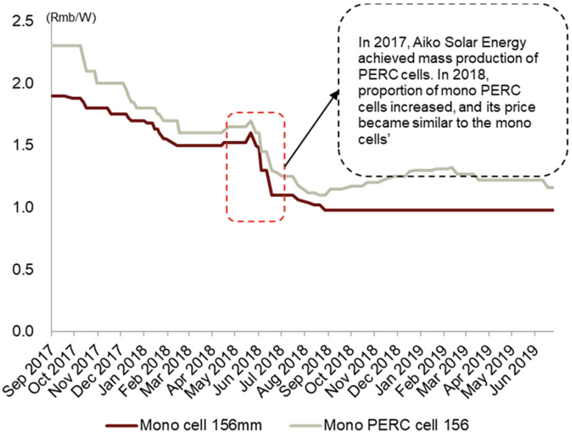


Fig. 4.5 Mono PERC solar cell prices versus mono solar cell prices. *Source* Solarzoom, CICC Research

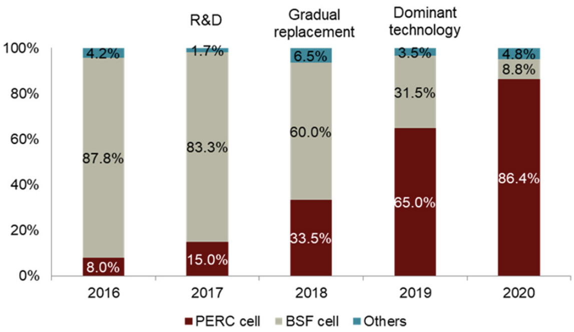


Fig. 4.6 Market share of different solar cell technologies (2016–2020). *Source* CPIA, CICC Research

continuously tried to cut costs by increasing the domestic production of core materials and continuously upgrading manufacturing technologies, enhancing product competitiveness, and enabling Chinese automotive battery manufacturers to capture a larger share of the global EV supply chain.

4.2.2.2 External Incentives and Incremental Market

Incentives for innovation in IoE and energy digitalization mainly include: (1) Profits from the incremental market created through business model innovation and digital empowerment; and (2) external incentives provided for energy infrastructure operators.

On the one hand, external incentives encourage traditional energy infrastructure operators to improve service quality through innovation. For infrastructure operators such as power grid companies, the value brought by innovation in IoE and energy digitalization is embodied in improved services provided for energy consumers, companies along the industrial value chain, the public, and governments. Specifically, this includes: (1) Assisting the government in scientific supervision, social governance, and smart city construction; (2) promoting the transition to clean and low-carbon energy, improving the level of electrification, and enhancing overall energy utilization efficiency; (3) making the power grid safer, more reliable, interactive, and open; (4) improving user experience and service quality; and (5) facilitating the modernization of the service industry chain and business transformation.

On the other hand, external incentives encourage various business entities in the incremental market to innovate service models and create new business formats. In addition to traditional energy services provided by infrastructure operators, companies could leverage energy digitalization to offer value-added services (e.g., energy efficiency management, virtual power plants, and energy trading) for energy consumers, information services (e.g., platform services and information consulting) for upstream and downstream companies along the industrial value chain, and derivative services (finance, e-commerce, and advertising) for the public.

4.2.3 Sources of Innovation

The ultimate goal of technological innovation in PV and EV batteries is to cut costs. However, the sources of innovation are diverse, either from the R&D undertaken in industrial research labs or from technological upgrading, occurring at various stages of the production process.

New products resulting from radical innovations drive technological revolution, undergoing years of research before being commercialized. The first two generations of PV technologies—crystalline silicon solar cell technology for power generation in the 1950s and thin-film battery technology in the 1970s—were created in developed areas such as the US and Europe. R&D and mass production of third-generation perovskite solar cells are well underway. Throughout the development of lithium-ion batteries, we note that each technological innovation contributed to higher battery efficiency and adapted to upgrades and changes in consumer demand at different stages. We believe team building and talent training are critical to radical innovation.

Incremental innovation seeks to optimize the performance of existing technologies based on expertise and experience accumulated during production; enterprises are the major driving force behind innovation. We note that companies along the PV industrial value chain try to strike a balance between higher efficiency and lower costs. Incremental innovation in lithium-ion batteries is manifested in an increasing percentage of domestic production of core equipment and upstream materials, and the growing use of lightweight materials for higher-energy-density batteries. The increased energy density of LFP batteries and ternary batteries led to a decline of about 85% in the cost of automotive battery packs during 2010–2020. We also believe that incremental innovations and enhanced dispatching capabilities of the power grid lay a solid foundation for IoE, enrich the application scenarios, and bring about more innovative business models.

Regarding sources of innovation in IoE and energy digitalization, the essence of these two sectors is energy internet of things (eIoT), which requires the integration of advanced information, communications, big data, artificial intelligence (AI), and internet technologies. Companies in the energy sector could leverage the power of the internet to transform their business models, and shift their focus from corporate business to consumer business to create a profitable incremental market.

4.2.4 Sources of Income

Gross margin improves on high R&D spending, and leading players are thus poised to gain excess profits. Comparing the leading domestic companies in the mono-Si wafer and polysilicon wafer sectors, we note that the wafer gross margin of Longi gradually surpassed that of GCL-Poly Energy over 2012–2015, due to the higher R&D expense ratio. We think that high R&D investment should bring innovation-based price premiums. However, such premiums are not sustainable over the long term as new entrants tend to acquire late-mover advantages. The gap in gross margin between Longi and Zhonghuan Semiconductor narrowed after Longi shared its diamond wire cutting technology throughout the industry (Fig. 4.7).

Another source of innovation income for IoE and digitalization comes from the incremental market, as well as cost reduction and efficiency enhancement in infrastructure.

Employing digital and smart technologies to improve grid operational efficiency and cut costs. Upon completing market-oriented reform in the power sector, profits of

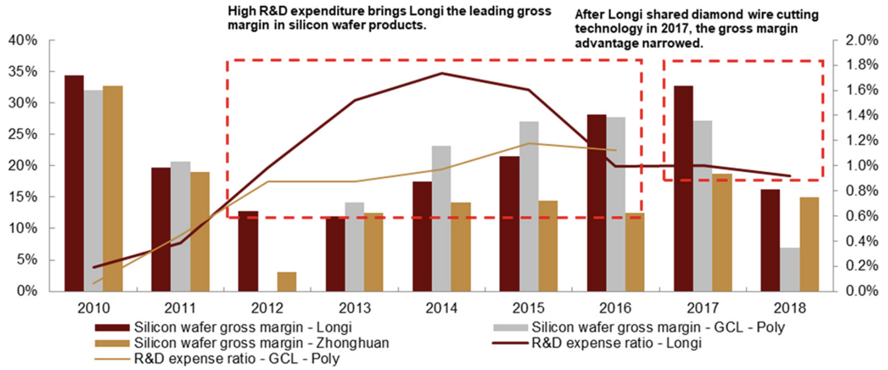


Fig. 4.7 High R&D investment brought about excess profits to Longi. *Source* Corporate filings, CICC Research

power grid companies mainly came from power transmission and distribution tariffs. Power grid companies have tried to manage an increasingly complex grid through digital transformation. Data assets, as the key driver to improve productivity, could be tapped to promote the transformation of business, operation, and management models, thereby reducing operational costs.

IoE and digitalization enable business model innovation and scale expansion to gain incremental profits. We think business model innovation could open an untapped market with less intense competition in which new entrants will bring new businesses and new customers. The potential profits could be on par with those of the platform-based internet companies. Typical new entrants include comprehensive energy service providers, distributed energy resources suppliers, customer service providers, and data-platform operators.

4.2.5 Sources of Funding

The sources of funding for innovation mainly stem from government assistance, long-term financing, and market investment.

In China, government assistance comes in two types—direct government subsidies and innovation investments made by state-owned enterprises (SOEs) in accordance with national development strategies or policy guidance. The former primarily aims at creating demand and expanding market size, thereby promoting industrial innovation and development. Such funds are granted to support industries with burgeoning demand and the need for incremental innovation, such as the EV and energy sectors. The latter is undertaken by SOEs to invest in innovative infrastructure projects that could generate positive externalities. Government-sponsored innovation funds are available to all eligible enterprises, regardless of their technical specialty.

Typical cases of government assistance are as follows. In the PV sector, the Chinese government offered renewable energy subsidies to attract more investment in downstream power stations to bolster PV demand. In the automotive battery sector, state and local EV subsidies have been granted since 2011, which, coupled with the waiver of the vehicle purchasing tax, has directly stimulated demand for EVs. In the IoE sector, the State Grid carried out R&D on power grid chips under the policy guidance to improve the performance of the smart grid.

Long-term credit or industry-specific long-term bonds could provide low-cost financing for key industries to support the innovation and development of enterprises. This form of financing is more suitable to the needs of larger-scale companies with relatively high credit ratings. Similar to government grants, such funding is not confined to a specific technology area.

Classic cases of long-term financing include: (1) Special loan scheme: In 2020, China Development Bank (CDB) provided a special loan of Rmb250bn to support the development of more intelligent, eco-friendly, and high caliber industry chains in the manufacturing sector, including the EV segment. (2) Carbon-neutral bonds: As of end-July, central and local SOEs issued 129 carbon-neutral bonds (a subcategory of green debt financing instruments in the China Interbank Bond Market), totaling Rmb134.89bn.

Another source of funding is market investment. In the primary market, VC and PE firms raise capital to support the radical innovation of select small- to medium-sized startups, particularly those with promising technologies and strong growth potential. In the secondary market, funds are raised through share placement to facilitate the mass production of new products.

Classic cases of market investment are as follows: (1) PE and VC institutions funded the R&D of PV cell manufacturing equipment. (2) CATL received investments from more than 20 institutions before their initial public offering (IPO). Judging from the firm's current stock price, these institutions earned a total of over Rmb40bn from this project. The floating profit of China Merchants Bank International Capital has exceeded Rmb17bn after two rounds of investment of nearly Rmb4bn.

4.3 Development of Green-Energy Industrial Value Chain

4.3.1 Recap of China's Attempts at Building a Green-Energy Industrial Value Chain

Government subsidies to stimulate end-market demand and enable domestic players to create economies of scale. To boost domestic demand, China has designed and implemented a variety of favorable policies (including subsidies and tax incentives for EV purchases). The government also issued a white list of batteries approved for use in EVs that would be eligible for subsidies, which enhanced the competitiveness of domestic manufacturers. With the expansion of the domestic market, the establishment of a sound industry chain, and growing economies of scale, domestic companies can engage in a variety of trial-and-error innovation projects as the market could accommodate the coexistence of different technology roadmaps. Economies of scale further push down costs. In a sufficiently large market, the marginal benefit for introducing an innovative technology is high. Companies seek to gain market share and returns on investment through cost reduction, and continue to invest in R&D to strengthen competitive advantages (Figs. 4.8 and 4.9).

Looking at the EV battery industry as an example, the government provides subsidies and tax breaks to fuel EV demand and facilitate the development of the domestic automotive lithium-ion battery industry. Demand for automotive lithium-ion batteries mainly comes from the EV sector. However, two factors dampened demand in the early stages of development. First, EVs were not an economical choice versus the fossil fuel vehicles. Second, batteries had a low energy density and delivered a shorter range for EVs. The government introduced a wide spectrum of policies, such as subsidies, waiver of vehicle purchasing tax, and issuance of free license plates to EV

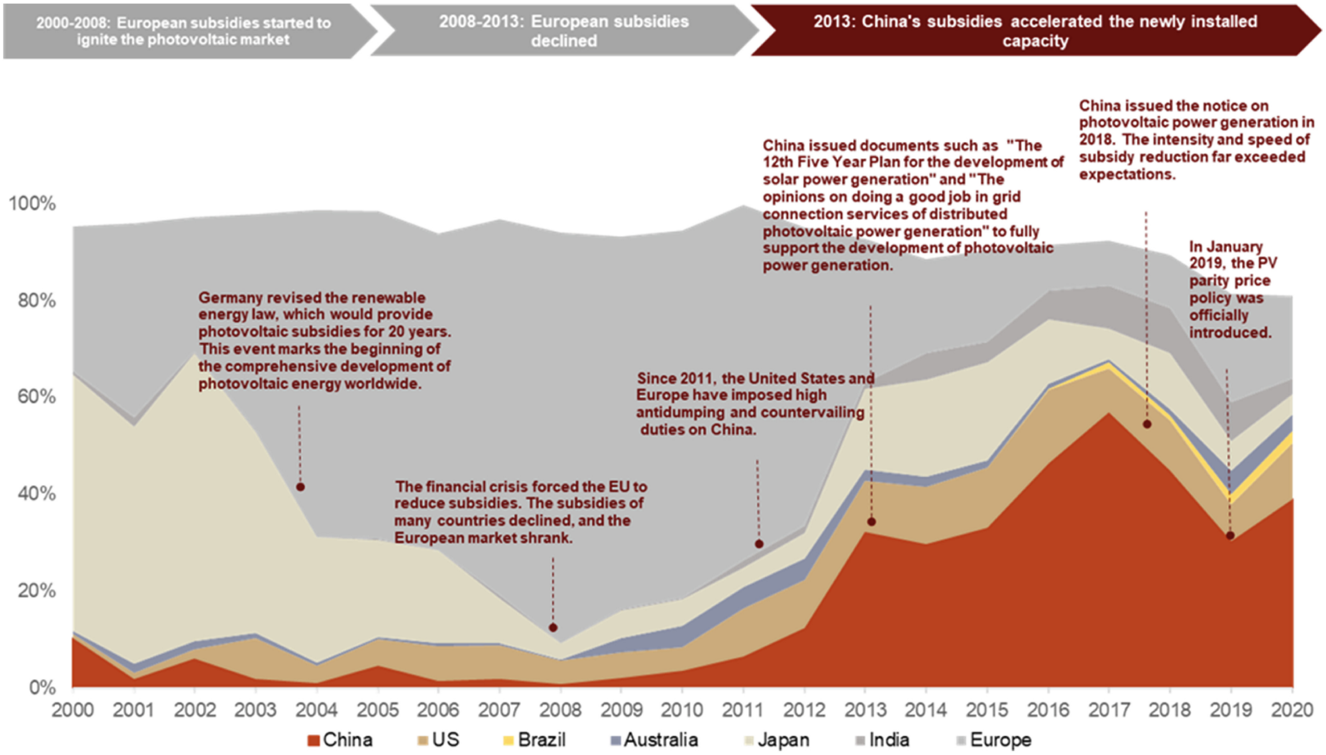


Fig. 4.8 Global newly installed PV capacity, by country; recap of major policies (1997–2020). *Source* BP, official government websites of countries in the above figure, CICC Research

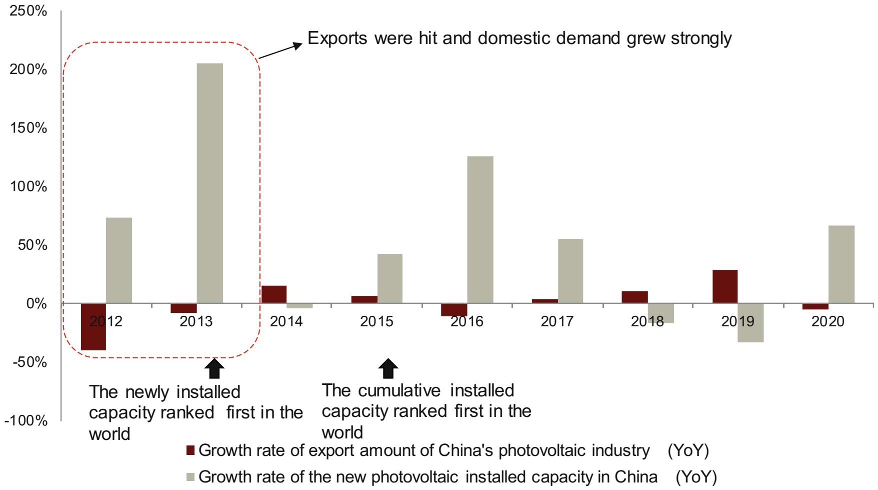


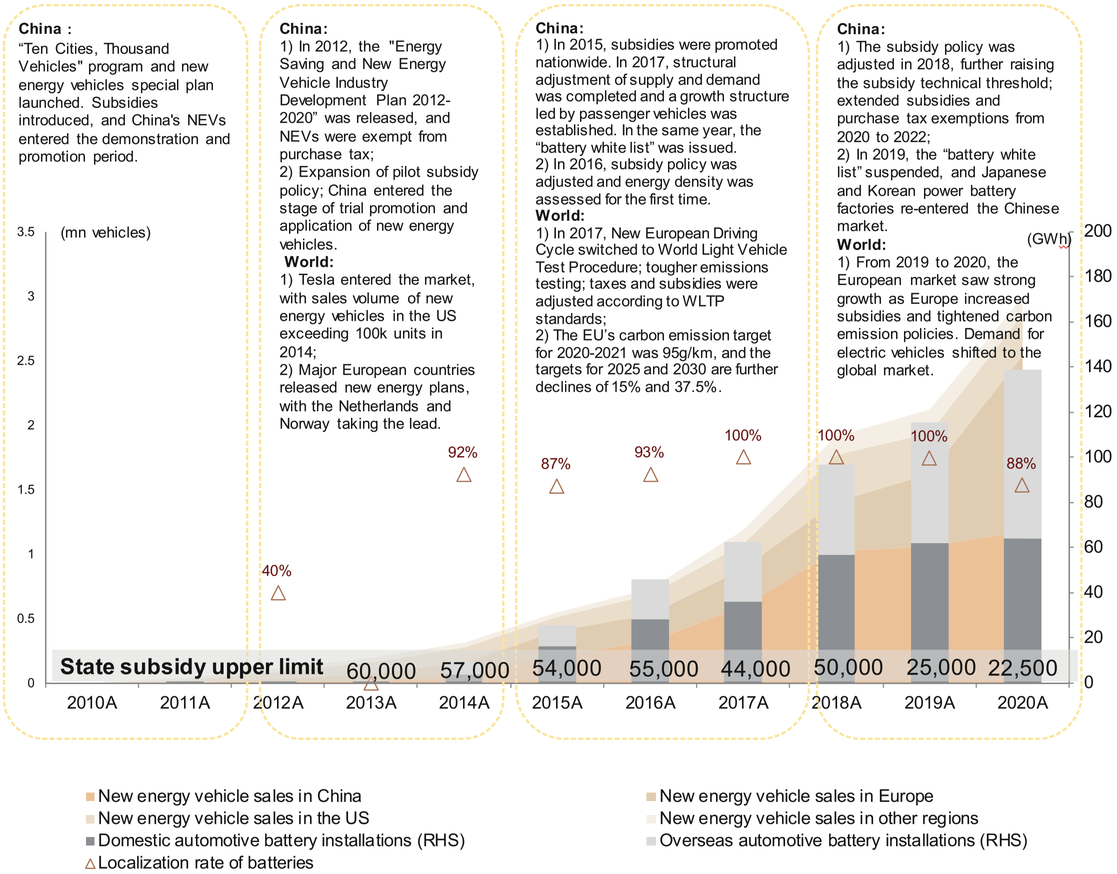
Fig. 4.9 Export value growth of China's PV industry versus growth of newly installed PV capacity. *Source* CPIA, BP, CICC Research

owners to increase the economic benefits of EVs, boost demand, and bring economies of scale to the domestic lithium-ion battery industry chain.

The government also issued a white list of batteries approved for use in EVs and eligible for subsidies, which enhanced the competitiveness of domestic manufacturers. The government also raised the technological threshold for receiving subsidies to encourage the upgrading of lithium-ion battery technology. China's EV sales volume increased nearly nine hundredfold to 1.17 mn units in 2020 from 1,400 units in 2010, resulting in a nearly a hundredfold increase in lithium-ion battery installation volume. EV and automotive battery assembly has mainly been concentrated in China over the past decade (Fig. 4.10).

In addition to providing subsidies, the government plays a leading role in guiding the direction of technological upgrading and providing a platform for experimentation. Companies along the green energy industry chain attach great importance to R&D and innovation, while the freedom to choose which technology roadmap to adopt is left to the market. The visible hand of government guidance and the invisible hand of a free market have worked together to facilitate the technological upgrading of the PV and automotive battery industries.

For the PV industry, the government has called for an increasing share of renewable energies in gross electricity consumption, and specified different provinces' responsibility for the level of consumption of renewable-energy-generated electricity. However, it does not spell out the exact proportion of PV and wind energy consumption. Those with lower cost would contribute to more renewable electricity generation. China released the *Guideline on Promoting Advanced Photovoltaic Technology Application and Industrial Upgrading* in 2015, in which clear requirements were set out regarding the conversion efficiency and attenuation rate of solar battery modules



China :
"Ten Cities, Thousand Vehicles" program and new energy vehicles special plan launched. Subsidies introduced, and China's NEVs entered the demonstration and promotion period.

China:
1) In 2012, the "Energy Saving and New Energy Vehicle Industry Development Plan 2012-2020" was released, and NEVs were exempt from purchase tax;
2) Expansion of pilot subsidy policy; China entered the stage of trial promotion and application of new energy vehicles.
World:
1) Tesla entered the market, with sales volume of new energy vehicles in the US exceeding 100k units in 2014;
2) Major European countries released new energy plans, with the Netherlands and Norway taking the lead.

China:
1) In 2015, subsidies were promoted nationwide. In 2017, structural adjustment of supply and demand was completed and a growth structure led by passenger vehicles was established. In the same year, the "battery white list" was issued.
2) In 2016, subsidy policy was adjusted and energy density was assessed for the first time.
World:
1) In 2017, New European Driving Cycle switched to World Light Vehicle Test Procedure; tougher emissions testing; taxes and subsidies were adjusted according to WLTP standards;
2) The EU's carbon emission target for 2020-2021 was 95g/km, and the targets for 2025 and 2030 are further declines of 15% and 37.5%.

China:
1) The subsidy policy was adjusted in 2018, further raising the subsidy technical threshold; extended subsidies and purchase tax exemptions from 2020 to 2022;
2) In 2019, the "battery white list" suspended, and Japanese and Korean power battery factories re-entered the Chinese market.
World:
1) From 2019 to 2020, the European market saw strong growth as Europe increased subsidies and tightened carbon emission policies. Demand for electric vehicles shifted to the global market.

Fig. 4.10 Development history of China's automotive battery industry. *Source* SNE, GGII, MIIT, CICC Research used for new PV projects. In addition, the Top Runner Program was designed to increase power generation efficiency by 1 ppt and promote the wider application of higher-efficiency PV products, which ended the phase of insufficient government support and guidance of China's PV industry. However, the government does not impose restrictions on the selection of specific technology roadmaps for PV modules. Instead, market competition comes into play—the technology that potentially generates greater economic benefits with lower costs will stand out and gain more market share.

For the EV battery industry, the government has continuously raised the technological threshold for receiving subsidies to guide the upgrading of lithium-ion battery technology in China. The EV subsidy policy issued in 2016 added a new eligibility threshold, stating that the energy density of batteries eligible for receiving subsidies shall not be lower than 90 Wh/kg, with larger amounts of subsidies tilted toward higher-energy-density batteries. The continuous increase in the energy-density threshold over 2018–2019 expedited the upgrading of the mainstream battery technology in China from LFP batteries to higher-energy-density, high caliber ternary batteries. This also motivated domestic battery companies to continuously upgrade the materials, manufacturing processes, and battery structures for LFP batteries and ternary batteries, and make technological breakthroughs in nickel-rich ternary cathode and LFP cathode materials, as well as the structural cell-to-pack (CTP) and cell-to-chassis (CTC) battery designs, leading to a continuous increase in energy density. During this process, the government did not intervene in the selection of technology roadmaps for automotive batteries, but allowed market forces to play a central role in selecting the most suitable technology roadmap to meet downstream demand.

At the same time, the government also adopts favorable policies to support the upgrading of infrastructure and the enrichment of application scenarios:

For the PV industry: As the power grid ensures reliable delivery of electricity to end-users, strengthening the construction of grid infrastructure boosts demand for PV installation and reduces wind and solar energy curtailment. The National Development and Reform Commission and the National Energy Administration jointly issued the *Clean Energy Consumption Action Plan (2018–2020)*, emphasizing the importance of improving grid infrastructure and giving full play to the role of the grid resource allocation platform. The ministries set the goal that the clean energy absorption rate (the percentage of the clean energy collected that can be absorbed by the power grid) would reach 95% by 2020. Since 2018, the renewable energy curtailment rate of the State Grid has declined year by year and remained below 5%. The proportion of renewable energy sources in total electricity transmitted by the 22 ultra-high-voltage (UHV) lines (18 operated by the State Grid and four by the China Southern Power Grid) has exceeded 30% since 2018.[1]

For the EV battery industry: In 2015, the State Council issued *Guidance on Accelerating the Construction of Electric Vehicle Charging Infrastructure*, and the

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[1] Source: National Energy Administration of China, Inner Mongolia Solar Energy Industry Association. https://www.gov.cn/xinwen/2023-02/14/content_5741481.htm.

National Development and Reform Commission released *Guidelines for Developing Electric Vehicle Charging Infrastructure (2015–2020)*. Meanwhile, local governments introduced subsidy policies for the construction and operation of charging stations to encourage third-party participation and improve the deployment of EV charging infrastructure.

4.3.2 More Policies Are Needed to Support Applications for Green Energy Technologies

4.3.2.1 Energy Storage

China's energy storage market is relatively small; as of 2020, cumulative installations of electrochemical energy storage systems accounted for less than 20% of the global total.[2] The major bottleneck stifling industrial development lies in insufficient demand, which we attribute to the lack of application scenarios and high cost. Specifically, downstream energy storage demand is mainly concentrated in areas such as supporting equipment for renewable power generation, large-scale grid storage, and user electricity-bill management. However, given the dominant position of coal-fired thermal power in China's electricity supply, the strong grid structure, and inexpensive end-user electricity prices, we think that the domestic energy storage industry faces headwinds in that it lacks profitable application scenarios. Energy storage (primarily electrochemical energy storage) projects in China are expensive, with a single source of revenue and few economic benefits. We estimate the IRR of PV energy storage projects at 4–5%, indicating weak organic growth. We think the current policies have partly drawn upon the successful experience from the development of PV and EV batteries, which require further fine-tuning and elaboration in order to remove the bottlenecks that impede the development of the domestic energy storage industry.

Top-level policies support the optimization of electricity supply mix and pricing mechanism, as well as the creation of application scenarios for energy storage. The government fueled demand for EV batteries by fostering the development of EVs. Similarly, China's pledge to achieve carbon peaking by 2030 and achieve carbon neutrality by 2060 is driving a massive expansion of renewable power generation to replace fossil fuels. We believe this will boost power consumption supplied from renewables, stimulate demand for grid ancillary services, and create application scenarios for power generation and grid-scale energy storage. The government also implemented peak and off-peak power tariffs, and improved the seasonally differentiated pricing mechanism. Given that the profit and cost of energy storage mainly depends on the arbitrage between the highs and lows of electricity prices, we believe that greater upside for user-end energy storage will be created by improving electricity-pricing policies.

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[2] Source: China Energy Research Society. White Paper on Energy Storage Industry 2021. https://www.cers.org.cn/site/content/b4a633ae713b962d075b48905c710460.html.

More effective policies are needed to bolster economies of scale and demand for energy storage. Once these scenarios have been developed and implemented, the core issue surrounding the demand growth is how to create economies of scale for energy storage as the existing policy support has been shown to be inadequate. In light of the development of PV and EV batteries and the experience at overseas energy-storage companies, we think policymakers could create opportunities for domestic energy storage companies to achieve economies of scale by: (1) Providing subsidies or low-interest loans for energy storage projects; (2) enabling energy storage participation in the wholesale electricity and ancillary service markets; and (3) establishing a sound electricity price mechanism for energy storage facilities to generate incremental profits.

Guiding the development of energy storage technology to meet diverse demand from a broad range of application scenarios. Downstream applications of energy storage technologies include electricity storage and energy storage for communications and data center infrastructure. Application scenarios of electricity storage encompass power generation, power grid, and commercial, industrial, and residential consumption. Demand for economic benefits and product performance varies in different scenarios. Thus, we think that the government should implement policies tailored to guide diversification of energy storage technologies, and strike a balance between high performance and cost saving on the back of more advanced technologies.

4.3.2.2 Hydrogen Energy

Bottlenecks hinder the development of the domestic hydrogen energy industry. 1. High cost of fuel cell and hydrogen energy applications. The selling prices of 10.5-meter and 12-meter fuel cell buses exceed Rmb2mn, while conventional gas-powered buses sell for around Rmb0.5mn. Hydrogen prices now range between Rmb60–80/kg, and the cost of hydrogen for a fuel cell vehicle is more than double the cost of gasoline for a gas-powered vehicle. Hydrogen energy applications in fields such as industrial heating and energy storage are even more expensive. 2. Reliance on overseas supply of key raw materials and components. China has achieved the import substitution of fuel cell systems and stacks, but it still relies on foreign supply of key raw materials such as proton-exchange membranes, catalysts, carbon paper, and carbon fibers used in hydrogen storage tanks. 3. Incomplete hydrogen energy industry chain and infrastructure. China has yet to establish a complete and efficient hydrogen industrial value chain that encompasses the entire production, storage, and distribution process. Coupled with poor hydrogen refueling infrastructure, this further hampers the large-scale application of fuel cell vehicles.

We believe that the upcoming Demonstration Applications of Fuel Cell Vehicles policy is similar to the PV feed-in tariff and EV subsidy policies. The new policy proposes increasing government procurement and subsidies to boost the sales volume of fuel cell cars and buses, which we think will help drive down costs, create new demand, and make hydrogen-powered vehicles more affordable for the public. The technological threshold for receiving the subsidies is raised under the new policy. Subsidies are tilted more towards medium- and long-haul and medium- and heavy-duty hydrogen-fuel-cell commercial vehicles. The new policy clarifies the major application scenarios for fuel cells, and underlines the importance of industry leaders in establishing demonstration city clusters and an industrial value chain. The government has also improved policy support for the construction and operation of hydrogen refueling stations, as well as demonstration projects for fuel-cell vehicles, and building a complete hydrogen energy and fuel cell industry chain.

4.3.2.3 Carbon Capture

We believe that carbon capture technologies hold the key to cutting carbon emissions in China's power and cement industries. Negative emissions technologies such as direct air capture with carbon storage (DACCS) and bioenergy with carbon capture and storage (BECCS) should be an integral part of the future energy system and will yield net CO_2 removal if deployed. The biggest pain point for carbon capture, utilization, and storage (CCUS) technologies is the high cost. For example, the installation of carbon capture devices will increase the cost of electricity by around Rmb0.4/kWh, making thermal power generation no longer economical. The cost of the first-generation CCUS technologies has fallen by nearly half over the past decade, contributing to sizable economies of scale and cost reduction. Thus, policy design mainly focuses on promoting large-scale demonstration projects for CCUS technologies and the construction of industrial clusters to reduce costs. The government has introduced tax incentives and subsidies tailored to national specificities to bolster the economies of scale of CCUS projects and maximize the benefits of emission reduction.

4.4 Comparative Risk Analysis of China's Green Energy Industry Chain

The major "horizontal risk" stems from the disruptive impact of the radical innovation of new battery technologies. We believe that the overall risk is manageable as there is no obvious R&D gap between Chinese companies and their overseas rivals. The "vertical risks" (which exist within the green energy supply chain for a particular generation of technology) mainly arise from equipment that requires import substitution, and from the scarcity of resources. We believe the overall risk is manageable, considering the following two factors. First, the gaps in the manufacturing of equipment and supplies of raw materials compared with foreign counterparts are relatively small. Second, the shortage of key resources could be partially addressed by leveraging new battery technologies such as sodium-ion batteries. Meanwhile, China boasts a complete PV and automotive battery industrial value chain to ensure stable supply and demand.

4.4.1 Analysis of Horizontal Risks

The major horizontal risk faced by China's green energy industry chain stems from the radical innovation of new battery technologies. Domestic PV and EV battery manufacturers are trying to cut costs further, and the radical innovation brought by new battery technologies should accelerate the rate of cost reduction. Specifically, PV technology focuses mainly on improving the power conversion efficiency of solar cells to reduce power generation costs. We believe that the third-generation PV cell technologies (as represented by perovskite solar cells), once industrialized, will have a disruptive impact on the existing crystalline silicon PV industry chain. We believe that the future of EV battery technology rests with solid-state batteries (significant improvement in safety levels; cost reduction potential) and sodium-ion batteries (cost reduction potential). Both are compatible with existing liquid-state lithium-ion battery manufacturing processes and equipment. The major risk confronted by domestic companies is the possibility of being overtaken by overseas key material suppliers. Overall, there is no obvious R&D gap between Chinese companies and their overseas rivals in terms of new battery technologies.

4.4.1.1 The Major Horizontal Risk for China's PV Industry Chain Lies in Third-Generation Perovskite Solar Cell

Third-generation PV cell technologies have a disruptive impact on the existing crystalline silicon PV industrial value chain. Crystalline silicon PV cell production adopts the vertical industry structure by which raw materials (silicon) are turned into final components (silicon-based solar cells) after a series of operations (e.g., silicon material production, crystal pulling, wafer slicing, and battery processing). In contrast, perovskite solar cells are assembled directly on glass substrates in a one-stop, layer-by-layer, spray-coating process.

PV industrial value chain may face disruptions from changes in core light-absorption materials. The groundbreaking perovskite solar cell technology may bring disruptions to crystalline silicon PV cell production, purification, processing companies, as well as manufacturers and consumables suppliers along the PV packaging material value chain.

Inducing changes in other general-purpose auxiliary materials. Conventional PV rolled glass is being replaced by ultra-white float glass coated with transparent, conductive oxide (TCO). The impact of third-generation PV cell technologies on the PV film segment is relatively small, with ethylene vinyl acetate (EVA) and polyolefin elastomer (POE) films still being widely used.

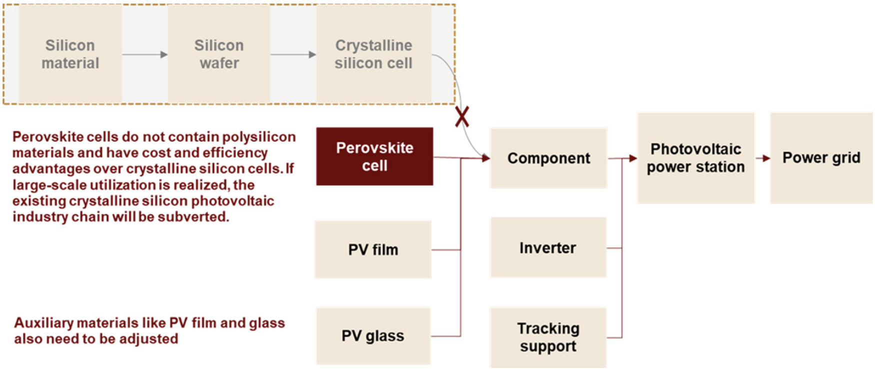

Fig. 4.11 Potential disruptive impact of perovskite solar cell on existing crystalline silicon PV cell industrial value chain. *Source* CICC Research

Incompatible with existing core equipment; back-end equipment may require further improvement. For equipment manufacturers, the preparation of perovskite thin films using liquid-phase spin coating or vacuum deposition techniques is not compatible with existing crystalline silicon PV production equipment. The back-end packaging process shares certain similarities with the crystalline silicon manufacturing process (Fig. 4.11).

Solar-cell efficiency tables published periodically in *Progress in Photovoltaics* show the progress of China's R&D in PV to be ahead of peers. We note that the efficiency records for single-junction perovskite solar micro-modules (close to the size for mass production) have been set by Chinese companies, with the latest conversion efficiency reaching 20.1%. Oxford PV has maintained the world efficiency record for lab-scale perovskite-silicon tandem cells, with the new cell efficiency record hitting 29.52% due to its perovskite and silicon-heterojunction tandem solar cell technology roadmap.[3] Chinese universities have led the industry in developing the perovskite-perovskite tandem solar cell technology roadmap, with the latest lab-scale cell efficiency reaching 26.4%.[4]

Chinese companies are global frontrunners in the mass production of perovskite solar cells. Three major companies engaged in commercializing perovskite solar cells, with Chinese companies maintaining leading positions in terms of production capacity and progress in capacity expansion. Corporate filings show that Hangzhou Microquant and GCL Nano (Chinese firms focusing on the single-junction perovskite solar cell technology roadmap), and Oxford PV (a UK-based firm focusing on the perovskite and silicon-heterojunction tandem solar cell technology roadmap) all plan to commission their 100 MW production lines in 2021 and 2022. Perovskite solar

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[3] Source: Oxford PV. https://www.pv-magazine.com/2020/12/21/oxford-pv-retakes-tandem-cell-efficiency-record/#:~:text=Oxford%20PV%20retakes%20tandem%20cell%20efficiency%20record%20Perovskite,certified%20by%20the%20U.S.%20National%20Renewable%20Energy%20Laboratory.

[4] Source: Solarbe. https://news.solarbe.com/202204/28/354285.html.

cells are mainly used in products that enjoy high price premiums, such as rooftop PV and building-integrated PV systems. In addition, Chinese PV glass, PV film, and solar cell manufacturing equipment companies have stepped up efforts to build labs for conducting research on perovskite solar cell applications. Hangzhou Microquant and GCL Nano plan to use self-developed or domestically produced manufacturing equipment in the mass production of perovskite solar cells.

4.4.1.2 Analysis of Horizontal Risks Within the EV Battery Industrial Value Chain: Being Overtaken by Overseas Rivals in Terms of Solid-State Battery Technology

From a long-term perspective, achieving the target energy density of 500 Wh/kg for high-end automotive batteries by 2035, in our view, means that Chinese firms must match them with high-energy-density electrode materials. However, such materials are incompatible with the current liquid-state lithium-ion battery system, which raise safety concerns despite improvements in battery performance. In contrast, the solid-state battery, which is intrinsically safer with better electrochemical stability, could match cathodes with voltages above 5 V and lithium metal anodes, pointing to high development potential. Specifically, quasi-solid-state and all-solid-state batteries with sulfides, oxides, and polymer electrolytes at the core each have their distinctive advantages, and we suggest closely tracking the technological progress and final application.

Separators, cathodes, anodes, and electrolytes may undergo technological upgrading, which only has a small impact on manufacturers in the near term. SES and Samsung have realized the production of solid-state batteries with energy densities of 450 Wh/kg and 900 Wh/L by using the NCM811 and NCM955 lithium-ion battery materials. Thus, we believe significant room remains for further development of ternary cathodes, and the future application is highly probable. Although the production of solid-state batteries with sulfide and oxide electrolytes will not employ the current separator and electrolyte systems in the future, we think it will take a decade for the large-scale application of solid-state batteries. During this period, the separator and electrolyte systems for quasi-solid-state batteries may undergo technological upgrading, but they will not be replaced in the near term, in our view. In addition, silicon carbon and lithium metal are both promising anode materials for lithium-ion batteries. We think the large-scale application of lithium metal anodes is unlikely to occur in the medium term.

Demands for production processes and equipment vary among different technology roadmaps for solid-state batteries; domestic technology roadmap could retain over 70% of the traditional liquid-state battery manufacturing techniques. The basic properties of solid-state electrolyte materials determine the development roadmap of solid-state batteries. Solid-state electrolytes are divided into three major categories: Polymer, oxide, and sulfide electrolytes. Five major technology roadmaps for quasi-solid-state batteries with hybrid solid-liquid electrolytes exist. Specifically, the sulfide-based electrolyte technology roadmap commonly adopted in Japan and South

Korea is incompatible with existing battery manufacturing equipment. It is still in the laboratory stage, and may take a decade before it is widely applied. In contrast, over 70% of the oxide-based quasi-solid-state battery technologies adopted by Chinese firms are compatible with traditional lithium-ion battery manufacturing processes and equipment.

China's EV battery industrial value chain faces two major risks amid the shift towards solid-state batteries. The first one is that the technology roadmap may be leading in the wrong direction. Solid-state electrolytes are divided into three major categories: Polymer, oxide, and sulfide electrolytes. Japanese and South Korean companies mainly focus on the sulfide-based electrolyte technology roadmap, while Chinese companies are inclined to adopt the oxide-based quasi-solid-state battery technology roadmap. The domestic technology roadmap should make full use of the existing production lines, and possibly realize a smooth transition toward a wider application of solid-state batteries; while the Japanese and South Korean technology roadmaps involve significant innovations in manufacturing processes and equipment. A consensus has yet to be reached on the maximum performance and technical difficulties of different technology roadmaps.

The second is that patents raise barriers to entry. Leading companies in the US, Japan, and other countries have secured the core patents on solid electrolyte materials used in solid-state batteries. The number of patents for solid-state batteries obtained by Japanese and South Korean companies far exceeds that obtained by Chinese companies. Leading players as represented by Toyota have built a dense network of patent rights around basic materials, which serves as a barrier to entry that impedes Chinese companies' overseas expansion.

4.4.2 Analysis of Vertical Risks

Vertical risks confronting the domestic green energy industrial value chain mainly arise from equipment that requires import substitution, and from the scarcity of resources. Specifically, core components and materials such as insulated-gate bipolar transistors (IGBT), n-type solar cell manufacturing equipment, low-temperature silver pastes, and silver powders are relatively dependent upon overseas imports. In the EV battery industrial value chain, domestic companies tend to place undue reliance on the overseas supply of key upstream resources such as lithium, cobalt, and nickel, as well as some imported equipment such as separators and copper foils. However, we think the overall risk is manageable, given: (1) The gaps in the manufacturing of other equipment and supplies of raw material compared with foreign counterparts are relatively small; and (2) the shortage of key resources could be partially addressed by leveraging new battery technologies such as sodium-ion batteries.

Vertical risks within the EV battery industrial value chain lie in the shortage of upstream lithium and cobalt resources. China is largely self-sufficient in the production of lithium-ion batteries, separators, cathodes, anodes, and electrolytes, with each segment accounting for over 50% of global supplies.[5] We think the current vertical risk facing China's EV battery industrial value chain lies in the shortage of upstream core resources such as lithium and cobalt. However, with the rollout of the sodium-ion batteries by CATL and the gradual industrialization of sodium-ion batteries in the future, we believe the shortage of key resources could be partially alleviated.

Root cause of China's supply risk stems from the uneven distribution of global resources; domestic lithium reserves mainly come from the lithium brine deposits in the Qinghai-Tibet Plateau; high-grade lithium mines are rare. Global lithium resources are abundant but unevenly distributed. The US Geological Survey (USGS) states that as of 2020, lithium brines in South America and lithium mines in Australia combined accounted for 65% of the proven global lithium reserves, and China's lithium reserves made up about 7%. Lithium brines—mainly located in Qinghai and Tibet—account for about 79% of China's total lithium reserves, while the high-grade hard-rock lithium deposits (21% of the nationwide total) are relatively rare. The lithium mining market is highly concentrated. In 2020, Australian lithium mines and South American lithium brines represented about 79% of global lithium supply, and China's lithium mines and brines accounted for about 10% of global lithium supply.[6]

Global cobalt resources are largely concentrated in Congo and Australia. The Democratic Republic of Congo is the clear leader among the world's top cobalt-producing countries, accounting for 68% of global output (0.14 mnt) in 2020. China's cobalt reserves made up only 1.1% of the global total, pointing to the scarcity of cobalt resources in China. Cobalt is widely used in battery materials, high-temperature alloys, and cemented carbides. Domestic cobalt demand mainly arises from the battery materials segment, accounting for 77% of the total.[7] Given the high proportion of battery materials in the downstream application of cobalt, we believe the strategic deployment of upstream cobalt resources is vital to the development of EVs.

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[5] Source: China Briefing. https://www.china-briefing.com/news/chinas-lithium-ion-battery-industry-overcoming-supply-chain-challenges/.

[6] Li, K., Wang, J. P. (2016). China's lithium resource development actuality and approaches. Resources & Industries, 18(1), 82–86.

[7] Han, J., et al. (2023). Current situation of cobalt resources and analysis of supply and demand situation in the next 5–10 years. Geology in China, 50(3), 743–755. https://doi.org/10.12029/gc20220918003.

Chapter 5
Biotechnological Innovation

Abstract Biotechnological innovations are rapidly reforming the pharmaceutical and agriculture sectors at home and abroad. With leading technological advances in the US and Europe, Chinese industries have been quick to follow with scientific discoveries, industrial applications, supply chain, legislation reforms, and administrative support.

Despite high pharmaceutical demand, China's manufacturing capability on the supply side is not yet globally competitive. The global pharmaceutical market is built upon the demand of unmet medical needs, health insurance, and extensive investment in new drug development. China is a leading pharmaceutical market in absolute size, but its pharmaceutical spending per capita is relatively low. Nevertheless, Chinese companies are catching up, and China's contribution to global pharma R&D has started to shift from high-quality generics to gradual innovation.

As for the agriculture sector, the overall supply in China is stable, but other countries' experience in agricultural innovation is also worth studying. China typically maintains steady output growth and a relatively high self-sufficiency ratio. However, there remains room for improvement in the supply of some agricultural varieties and in the front-end sector of the meat value chain. We think China's overall biotech innovation in the agriculture industry is characterized by incremental innovation. Judging by China's successful innovations in rice cultivation, we think policy support, appropriate government mechanisms, and public–private cooperation are important for agricultural R&D.

Agriculture and pharmaceutical sectors are now at different stages of innovation, and therefore need different types of policy support. Major factors affecting China's pharmaceutical innovation and status quo are basic science development, clinical R&D, and standardized production capability. Policy-wise, we believe: (1) Funds from the public sector could be used to support the development of basic and translational sciences, which are the foundation for innovation; (2) pharmaceutical payment reform could be accelerated, and incremental funds from commercial insurance be introduced (3) a tiered financing system could be built to enhance risk-resistance capacity; and (4) a new drug approval system could be optimized to encourage innovation.

CICC Research, CICC Global Institute, *The Rise of China's Innovation Economy*,
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As for biotech innovation in agriculture, policy support may include the following. (1) Legislative supervision: We suggest that the government enhance the protection of agricultural intellectual rights and step up efforts in combating infringements. (2) Capital investment: We suggest that public sector investment in R&D be increased and cooperation enhanced with the private sector. (3) Talent education: We propose strengthening whole-procedure education and the cooperation between companies and research institutes.

5.1 Challenges and Opportunities in China's Biotech Innovation

Biotech innovations are vital for advances in both the pharmaceutical and agricultural sectors. Developed countries are still leading in pharmaceutical innovation, but China is catching up. As for agriculture, food supply is overall stable, but bottlenecks remain.

5.1.1 Biopharmaceutical Innovation: Chinese Companies Catching Up

5.1.1.1 Pharmaceutical Market from a Global Perspective

The US is now the world's largest pharmaceutical market, and a majority of drug spending in the US is directed toward innovative drugs with clinical value. As assessed by Institute for Clinical and Economic Review (ICER), US consumers are on average willing to pay US$100,000–150,000 for a quality-adjusted year of life. In 2019, drug sales revenue in the US reached US$495bn, the highest in the world. In 2020, 67% of the top 5 global medicines by sales value were sold in the US. According to Pharmaceutical Research and Manufacturers of America (PhRMA) and IQVIA, original medicines accounted for 10% of prescription volume and 80% of sales value in the US in 2020, and the share of original medicines with patent protection and prescription medicines reached 66% in 2018 (Fig. 5.1).

China is a leading pharmaceutical market in absolute size, only smaller than the US and EU, but its pharmaceutical spending per capita is relatively low. According to *China Health Statistics Yearbook* and OECD, in 2019, health spending and medicine

Global sales	Drug	Company	Approval time				Sales in 2020 (% of global	
			US	EU	Japan	China	US	ROW
1	Adalimumab Humira	Abbvie (US)	Dec 2002	Sep 2003	Apr 2008	Jul 2010	81.2%	18.8%
2	Pembrolizumab Keytruda	MSD (US)	Sep 2014	Jul 2015	Sep 2016	Jul 2018	58.1%	41.9%
3	lenalidomide Revlimid	BMS (US)	Dec 2005	Jun 2007	Jun 2010	Jun 2013	68.5%	31.5%
4	Ibrutinib Imbruvica	Abbvie/J&J (US)	Nov 2013	Jan 2014	2016	Aug 2017	56.3%	43.7%
5	Apixaban Eliquis	BMS (US)	Dec 2012	May 2011	Dec 2012	Apr 2013	59.8%	40.2%

Fig. 5.1 Global pharmaceutical market. *Note* ROW refers to rest of the world. *Source* FDA, CICC Research

spending per capita in China stood at around US$700 (6.67% of GDP) and US$260, while those in the US reached US$12,000 (17.6% of GDP) and US$1,128 (only considering prescription medicines). However, China's medicine spending mix has been changing since reforms on drug approval and the medical insurance system started in 2015. We see great potential for innovative medications as the spending mix and payment system shift away from generic drugs, traditional Chinese medicine (TCM) injections, and adjuvant drugs due to the evolving commercial insurance system in China.

New medicine R&D and commercialization are key focuses of the pharmaceutical industry, which are now dominated by European and US multinationals. Developing new drugs requires extensive investment. In Europe and the US, after completing proof-of-concept work, small and medium-sized pharmaceutical companies often choose to collaborate with multinationals boasting ample cash, clinical experience, and commercialization platforms, either through joint development or authorization. This leads to further domination of new drugs by European and US multinationals. According to PharmExec and Torreya, revenue at global top 20 pharmaceutical firms reached close to US$600bn in 2020.

Chinese pharmaceutical manufacturers are catching up. Compared with European countries and the US, the pharmaceutical manufacturing industry started late in China, and its pharmaceutical market remains segmented. Domestic leading pharmaceutical manufacturers mainly provide generics, and most of their new drugs cannot compete with international rivals. Biomedicine and biotech companies focusing on innovative drugs are also in the growth stage.

5.1.1.2 Chinese Companies Catching up in R&D and Marketing

Developing a new drug involves various academic disciplines such as basic science, translational medicine, pharmaceutical science, and clinical medicine. After the drug targeting strategy is decided, scientists conduct preliminary screenings to select a single molecule from thousands or millions of candidates, on which clinical research will be conducted. The clinical phase I, II, and III research on candidate molecules are also necessary to verify their effectiveness and safety for adaption diseases. The new drug may then enter the market after gaining approval from regulators and an expert committee (Fig. 5.2).

New drug R&D features extensive investment, long periods of time, and low success rates. Trial-and-error efficiency is the core competency after drug screening begins. For innovative medicine R&D projects launched after 2010, it may take 8–10 years of R&D of 5,000–10,000 types of compounds to roll out one new drug. Average R&D cost per drug is over US$1bn, most of which is spent on clinical trials.

The US is a major contributor to global medicine innovation. According to the 2021 PhRMA member annual survey, this trade group's member companies invested US$91.1bn (21.4% of sales income) in R&D in 2020, accounting for 49% of global medicine R&D spending. In addition to large pharmaceutical firms, private sector investments and government-led US National Institutes of Health funding are also

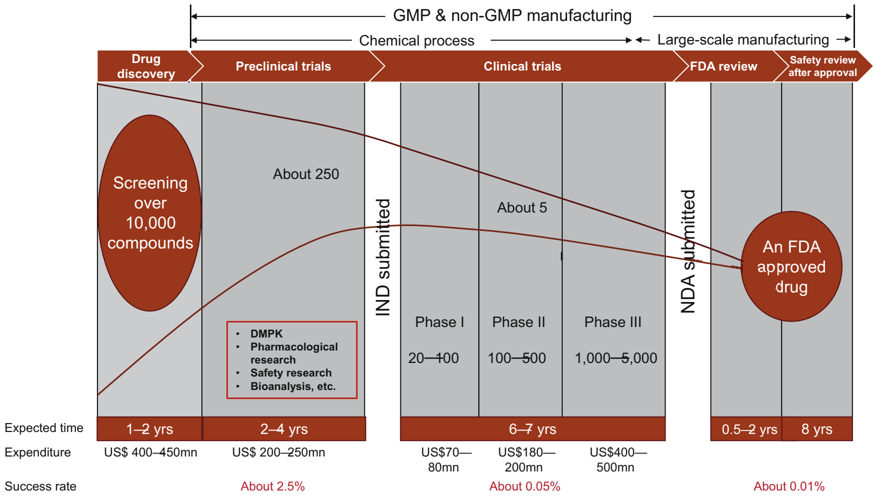


Fig. 5.2 New drug R&D. *Note* DMPK refers to drug metabolism and pharmacokinetics. *Source* Frost & Sullivan, CICC Research

major sources of R&D spending in the US. High-quality, proactive innovation gave rise to innovative biotech companies and pharmaceutical giants in the US. In 2020, 51% of new drug molecules and nine of the global top 10 best-selling drugs were launched by US companies, and nine of the global top-20 pharmaceutical companies were headquartered in the US. As of March 22, 2021, 46% of biotech companies were based in the US (Figs. 5.3 and 5.4).

Chinese pharmaceutical companies used to spend more on marketing than on R&D due to the high cost of gaining approval for new drugs and a lack of policy support. While drug approval reform has brought significant changes, the share of R&D spending at leading domestic pharmaceutical companies remains lower in China than in Europe and the US. Beigene invested Rmb8.45bn in R&D in 2020, a record

Fig. 5.3 Share of R&D spending in drug sales. *Source* OECD, IQVIA, CICC Research

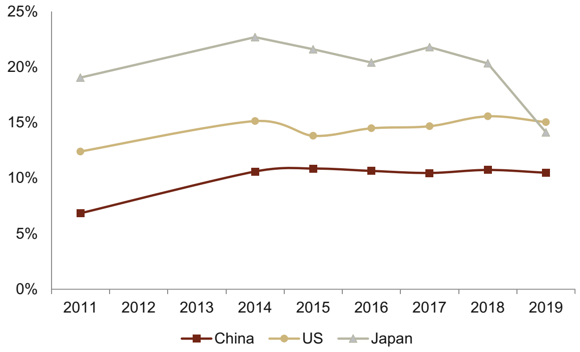
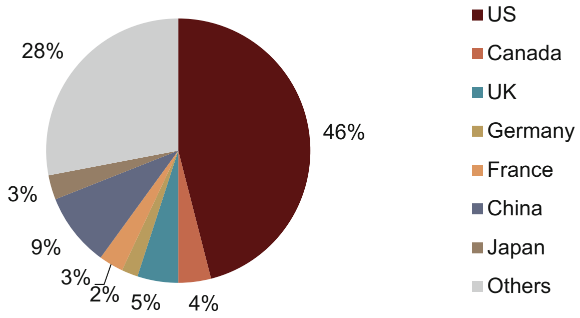


Fig. 5.4 Country of origin for companies developing new drugs (2021). *Source* Deloitte, CICC Research



for Chinese pharmaceutical companies. Meanwhile, traditional large pharmaceutical companies such as Hengrui also started stepping up innovation in 2016.

Chinese pharmaceutical companies see opportunities to catch up with foreign rivals. Domestic companies are competitive in drug discovery technologies including drug screening platforms and drug screening AI technologies. In addition, new modalities including cell therapies, gene therapies, and bispecific antibodies are making significant progress in drug discovery. China is only second to the US in terms of the number of clinical trials of cell and gene therapies. Legend Biotech achieved an agreement with J&J to jointly develop BCMA CAR-T Carvykti in 2017, and it was approved by the US Food and Drug Administration (FDA) and the European Commission (EC) in 2022. China's biotech companies have rich experience in biomedicine and tumor immunology, and many were deployed in the bispecific antibody for tumor immunology. Domestic company AkesoBio released positive results of its PD-1/CTLA-4 bispecific antibody AK104, and the drug was approved for the treatment of cervical cancer in 2022 by the National Medical Products Administration (NMPA).

The large population and strong demand potential in China provide a solid foundation for domestic innovative drug companies to achieve commercialization and expand into the larger overseas market. Since joining the International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use (ICH) in 2017, China has gradually switched to international standards for the regulation and development of innovative drugs, and domestic innovative drug companies are also entering the global market.

Chinese companies are expanding overseas teams for clinical research and marketing. More and more domestic companies began to conduct clinical research abroad to better support product launches and sales in global markets. The number of overseas countries in which Chinese pharma companies conducted clinical trials and the total overseas clinical trial projects rose from 14 and 48 in 2015 to over 50 and 340 in 2019. Beigene gained approval for marketing Zanubrutinib in the US in 2019, and other Chinese companies such as Hengrui are also developing overseas marketing systems. We expect more domestic pharma companies to go global.

5.1.2 Agriculture Supply in China: Stable Overall, but Capacity is Weak in Front-End Sectors

China's agricultural production is characterized by its large scale and stable supply. However, conditions vary for specific varieties. For example, although the supply of major grains is stable, feed grains supply is less secure. In addition, although China is able to secure its meat supply, there are front-end weaknesses in areas such as breeding. As a result, we see higher risks in front-end sectors of the agricultural value chain.

5.1.2.1 Overall Supply Stable; Conditions Vary Among Varieties

China is the world's biggest grain and meat producer, with its share of grain and meat produced accounting for 21% and 23% of global output in 2019 (Figs. 5.5 and 5.6). Output of grain and meat has grown steadily. Data from the National Bureau of Statistics (NBS) shows that the country's total grain output in 2020 was 669 mn tonnes, growing at a 10-year CAGR of 1.8%. Total meat output in 2020 was 77.48 mn tonnes, corresponding to a CAGR of -0.31%. Total meat output in China dropped 10% YoY in 2020, dragging CAGR, as African swine fever (ASF) harmed hog production capacity.

Agricultural supply in China is guaranteed. First, per-capita grain and meat supply is high. According to the Ministry of Agricultural and Rural Affairs, China's grain

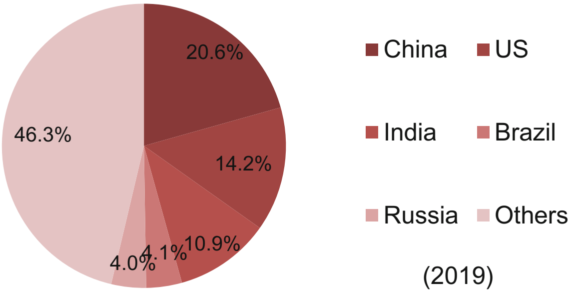


Fig. 5.5 Share of global grain output by country. *Source* FAO, CICC Research

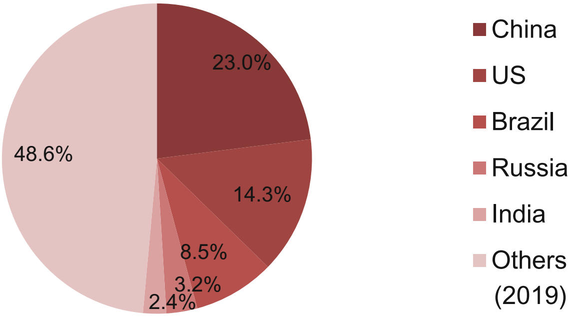


Fig. 5.6 Share of global meat output by country. *Source* FAO, CICC Research

supply per capita reached about 480 kg in 2020, exceeding the international safety standard of 400 kg by 20%. The Food and Agriculture Organization of the United Nations (FAO) said China's annual meat supply per capita was 54.4 kg in 2020, surpassing the global average by 28%. Second, self-sufficiency rates are high. The Organization for Economic Co-operation and Development (OECD) and FAO estimated China's grain and meat self-sufficiency rates at 81.0% and 90.6% in 2020, which suggests domestic supply could fully meet demand. Third, the inventory to consumption ratio is high. China's inventory to consumption ratio is 56.2%, exceeding the world average by 29.1 ppt.

The production structures of grain and meat are concentrated, while supply capacities differ. Rice, wheat, and corn are the main grain products in China, but soybean output is low. Pork and poultry are China's major meat products, while the production of ruminant meat is low. The supply capacity of different agricultural products varies, in our view:

First, supply of rice and wheat (main staples) is ample and stable. China's self-sufficiency rate is almost 100% for both rice and wheat, while rice and wheat supply per capita meets or exceeds the world average. As for rice and wheat yields, China not only outperforms the global average, but also surpasses average levels of major global rice and wheat producers. Overall, China has secured the supply chain of rice and wheat.

Second, supply of corn and soybean (main animal feeds) is relatively weak. The situation is better for the supply of corn than it is for soybean, but there are problems in corn seed breeding. China's self-sufficiency rate for corn stands at 89%, and its per-capita corn supply beats the world average. However, corn's inventory to consumption ratio is low compared with that of other grain products, which confirms that corn supply is weaker than for rice or wheat. Meanwhile, the corn yield is lower than main producers, and thus we believe China still has weaknesses in corn seed breeding. Soybean sector faces weak supply and front-end bottlenecks. China's soybean self-sufficiency rate is 18%, while its soybean yield meets or exceeds 70% of the global average. Thus, we see weaknesses in soybean supply and seed breeding.

Third, supply of hog and poultry is strong, but breeding capacity is weak. In China, hog and poultry self-sufficiency rates both exceed 90%, and per-capita supply is high. However, China underperforms the global average and major hog and poultry producers in terms of yields, and its share of global hog and poultry breeding markets is relatively small. In our view, this highlights China's inefficiency in hog and poultry breeding.[1]

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[1] Source: FAO, OECD, NBS, US Department of Agriculture (USDA), World Bank, Ministry of Agricultural and Rural Affairs of China, Difference comparison on land intensive use of different scale farmers in rice-growing areas in Southern China by Liu, C. et al. (2018). Study on management scale and technical efficiency of grain farming households by Jia, L. (2017).

5.1.2.2 Supply is Weak at the Front End

Risks in China's agricultural supply chain may be classified into vertical and horizontal risks, both of which call for biotech innovations. Vertical risks refer to risks in seed production and breeding, which may be offset through technological upgrades. Horizontal risks mainly include low efficiency and disease-related risks. We attribute the low production efficiency in the agriculture sector to small business scale, and suggest that the country support business expansion with favorable policies and engage in technological innovation on economies of scale. To reduce risks related to animal diseases, we think the sector could innovate in disease control-related technologies and expand operating scale to improve disease resistance.

Vertical risks in seed production and breeding could be reduced by improving competitiveness and innovation. China's competitiveness in agriculture's front-end sectors (seed production, seed breeding, hog and poultry breeding, for example) is relatively weak. For grain, yields of feed products in China are lower than the average of global leaders. We believe that Chinese companies in this sector could be better at innovation. For meat, China has to improve the genetic qualities of its sows because piglets weaned per sow per year (PSY) and average carcass weight are lower than animals from European countries and the US. We think technological R&D is crucial, and that innovation will bolster front-end supply first, and then the supply along the entire agricultural value chain.

Low efficiency caused by small business scale is a kind of horizontal risk. To fuel innovation and reduce such risk, favorable policies that promote business expansion are needed. Small farms dominate the agricultural production market in China. Results of the third agricultural census of Ministry of Agricultural and Rural Affairs shows that around 98% of producers in China are small farms, but arable land per farm only averages 7.8 mu (1 mu equals around 666.67 m^2). According to *China Animal Husbandry and Veterinary Yearbook*, per farm hog inventory stands at nine, and around 57% of farms operate a large-scale hog business. In recent years, China dealt with problems such as arable land fragmentation by deepening land reform. It also stepped up efforts to promote the transfer of land operating rights and improve farming efficiency. We think business expansion will likely accelerate in the agriculture sector, and economies of scale will bolster technological innovation.

Disease-related risk, as another kind of horizontal risk, could also be reduced through business expansion and biotech innovation. In our view, large-scale business operations could enhance companies' disease control and prevention capability, as well as management. In addition, we expect companies to strengthen technological innovation in fields such as insect-resistant traits and animal vaccines.

China could improve supply in its seed production sector, and biotech innovation could play a vital role. Our estimation for the average gross margin (GM) of seed production and fertilizer industries in major economies was 43% and 47% in 2020, significantly higher than the GM for pesticides and crop production sectors. We calculate that the R&D expense ratio of seed production sectors in major economies is 14%, the highest along the industry chain. This shows that R&D and innovation play important roles in the development of the seed production business. The industry in

China faces smaller-scale business and uncertainties in supply, and the R&D expense ratio of China's seed production sector is low. We think China needs to catch up with other countries in terms of seed production.

Also, China could strengthen the competitiveness of the breeding industry through R&D. We estimate the average GM of the animal breeding and health care sectors in major economies to be 53% and 59%, significantly higher than the GM of the feed and farming businesses. The average R&D expense ratios of the breeding and animal health care businesses reached 12% and 8% in 2020, which are the highest in the animal farming industrial value chain. We think these two sectors are driven by R&D. Compared with peers elsewhere, Chinese breeding companies record relatively lower revenue, reflecting their weak competitiveness and supply. The total revenue of China's animal health care sector is also low, but China is competitive due to its strengths in hog vaccines (overseas peers mainly focus on ruminate vaccine R&D).

China's low supply in seed production and animal breeding sectors affects market stability. Cropping value chain: Supply is weak in the seed production sector while demand is stable. To analyze the supply stability of China's cropping sector, we use demand stability factor α (α = China's share in the global grain production market/ China's share in the global grain consumption market) and supply stability factor β (β = China's share in the global seed production market/China's share in the global grain production market) to reflect the country's capability to meet grain demand and add support to grain production in the seed production process. According to our calculations, the US and France have α values exceeding 1, reflecting strong demand stability. The α value for China is less than 1 due to the reliance on soybean imports. We think overall grain demand in China is stable, given that demand for the main grains is stable. The β value in the Netherlands, France, and the US exceeds 1. China underperforms these seed production leaders in terms of supply, but its β stands at a relatively high level due to low R&D expenses. We expect Chinese companies in the industry to step up R&D efforts. Overall, demand is stable in China's cropping sector, but stability of supply in the seed production sector needs further improvement.

Animal farming value chain: Demand is solid while supply in the breeding sector is relatively weak. We use the same calculation method for this sector. Most countries have similar α values, which are close to 1. In contrast, China's α value is less than 1 due to its reliance on imported beef. Thanks to its large-scale hog and poultry production, the overall demand in the animal farming sector is secured, in our view. The β values of the US, Germany, the UK, and the Netherlands are significantly higher than 1, but China's is 0.38. This reflects relatively unstable supply along the animal farming value chain, which should be mainly attributed to the low sow capacity. Overall, we think demand is stable in the animal farming sector, while breeding capacity should be improved.

5.2 Insights into China's Innovation in Pharmaceutical and Agriculture Sectors

We look into China's biotech innovations in the pharmaceutical and agriculture sectors, and provide policy suggestions accordingly. Major factors affecting China's pharmaceutical innovation and status quo are the level of basic science, clinical R&D, and standardized production capability. To encourage innovation in pharmaceutical manufacturing, the government could focus on building value-oriented incentive mechanisms and an efficient capital market, in our view. Regarding the agriculture sector, the government could mainly focus on incremental innovation while occasionally introducing radical innovations. Favorable policies, governmental mechanisms, and cooperation between the public and private sectors are conducive to biotech innovation in agriculture, especially for seed production, breeding, and vaccine development.

5.2.1 Analysis of Factors Affecting China's Pharmaceutical Manufacturing Innovation: From Labs to Production and Supply

Development of basic disciplines, pharmaceutical R&D spending, and trial-and-error efficiency during the development stage are important factors affecting the global competitiveness of pharmaceutical manufacturers. An efficient, standard supply chain is the foundation, in our view. Development of basic disciplines is relatively slow in China. While policy guidance has become increasingly clear since the drug approval reform in 2015, we believe stimulus for drug innovation remains insufficient.

Basic science is decisive for original innovation. Drug R&D is a continual process from basic disciplines to clinical development. Innovation of medicine targets and mechanisms mainly rely on high-quality basic research, and the conversion of basic research results into clinical research requires a mature system. Pharmaceutical companies, however, play an important role in clinical trials and commercialization.

There is room for improvement in basic research and translational science in China. China's reform of its drug approval system encouraged pharmaceutical companies to recruit more experts in clinical trials and pharmaceutical production. However, China still lags the US in academic research, and the conversion of academic results into actual product rollout is slow. According to OECD, China's R&D expenditure as a percentage of GDP has remained above 2% for several years, for instance, 2.1% in 2018, close to that of the UK and France. However, most of the expenses were used to fund clinical trials, which accounted for 67% of the expenditure in 2016. Only a small proportion was reserved for basic research in China, well below that of Europe, the US, and Japan, which allocate 10–20% of their R&D expenditure to basic research.

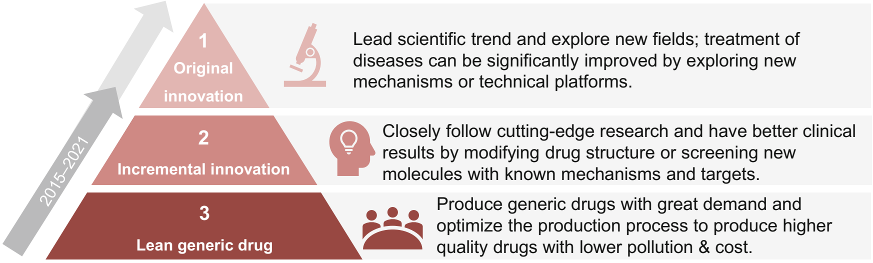


Fig. 5.7 Three stages of innovation. *Source Building a Sustainable Ecosystem for China's Pharmaceutical Innovation*, 2016, China Pharmaceutical Enterprises Association, China Pharmaceutical Industry Association, China Chamber of Commerce of Medicines & Health Products Importers & Exporters, R&D-based Pharmaceutical Association Committee, CICC Research

It takes time to catch up. The fast-follower strategy may help strengthen China's basic research at certain stages, but may in the long run cause low efficiency. We believe the fast-follower strategy is an important way for domestic pharmaceutical manufactures to build an innovation system from scratch, leveraging their late-mover advantage in the medium to long term. In the long run, we think the capability for original innovation and upgrades based on basic and translation sciences is a prerequisite for domestic pharmaceutical firms to establish global competitiveness in new drug R&D (Fig. 5.7).

The innovation of pharmaceutical manufacturing requires funding and incentives. While the pharmaceutical manufacturing industry has been developing for more than 100 years abroad, China only began to build its own production system for medicine ingredients, preparations, and generics in the twentieth century. The Chinese government has, since 2008, launched major projects such as new drug innovation to encourage innovation in pharmaceutical manufacturing. The innovation ecosystem gradually improved after the drug approval reform started in 2015.

Chinese pharmaceutical companies are rapidly catching up with overseas peers in innovation. Domestic pharmaceutical manufacturers have been expediting new drug innovation since 2015, and some early starters have begun to see rewards for their efforts. As of end-2020, China accounted for 13.9% of the global new drug pipeline by number, ranking No. 2 in the world. Meanwhile, a large number of emerging and transforming pharmaceutical companies are going after similar drug targets against the backdrop of an immature system for basic science and R&D. In order to build a globally competitive innovation pipeline, companies might need to switch to higher-value best-in-class (BIC), and first-in-class (FIC) drugs, in our view.

We believe value-oriented incentive mechanisms and an efficient capital market are major driving forces for pharmaceutical companies to deploy high-risk and high-value advanced innovations. Commercial value is the key factor for drug R&D spending, and developing BIC and FIC medicines usually involves higher risks. As new drugs are mostly first rolled out in the domestic market, we think offering a premium price for high-risk innovations will encourage more pharmaceutical companies to invest in innovative fields. In the realm of the capital market, developing novel drugs entails considerable uncertainty and risk, especially during the initial stages of research and development. This kind of undertaking represents a form of venture capital, and the securitization of these projects could help to distribute the risk.

Pharmaceutical payment system is not diversified in China, and we see upside in domestic pharmaceutical demand. National medical insurance is the largest public medicine payment system, and its priority is to satisfy basic medical needs by ensuring the affordability of medications. New medicines such as PD-1 monoclonal antibody (McAb) are priced markedly lower in China than abroad. In addition, a high proportion of medical expenses in China is not reimbursable, implying domestic patients are not yet fully motivated by the national healthcare payment system to pay for medical treatments and medicines. Commercial insurance is an important supplement to public healthcare funding, but the lack of medical data has impeded the development of commercial insurance in China.

China's healthcare capital market in rapid boom. Pharmaceutical companies face less difficulty in raising funds following the gradual improvement of the secondary market system, but we think some domestic biotech companies are overvalued. Data from vcbeat.top shows funds raised for healthcare projects from the domestic primary market totaled US$19.35bn in 2018 and US$15.45bn in 2019, close to the levels in the US in the same period. The Hong Kong Main Board Rule Chapter 18A and sci-tech innovation board provides an opportunity for biotech companies to be listed domestically. In 2020, proceeds from domestic pharmaceutical IPOs markedly increased to Rmb62.7bn, but remained lower than in the US.

Preclinical R&D in China features low costs but high efficiency. According to The Ministry of Education of China and National Center for Education Statistics (NCES), biomedicine undergraduates and postgraduates totaled around 0.34 mn in China, higher than in the US in 2019. This makes low-cost but efficient R&D for innovative drugs possible.

Thanks to a visible competitive advantage, domestic contract research organizations (CRO) companies have received abundant overseas orders for preclinical R&D services. After China joined the WTO in 2001, domestic CRO such as Wuxi AppTec began to take on preclinical lab research for overseas innovative drug companies. In 2020, China accounted for 20.4% (US$2bn) of the global preclinical R&D outsourcing market. Providing CRO services also helped domestic firms develop a large number of experienced engineers (Figs. 5.8 and 5.9).

Improved regulation of clinical trial approval expedites the use of clinical resources. Regulation of clinical trial application began to be loosened in 2015, and scrutiny of clinical data has since been strengthened to avoid stockpiles of low-quality applications. In addition, there is a rising number of clinical trial agencies in China to ensure high efficiency. The time it takes to acquire approval for clinical trials in China was shortened from 6 months to 60 workdays in October 2017. However, the clinical resources are not fully utilized in China due to the duplication of industry development at different stages. In 2019, the US had 550 drug targets in clinical trials (vs. 160 in China).

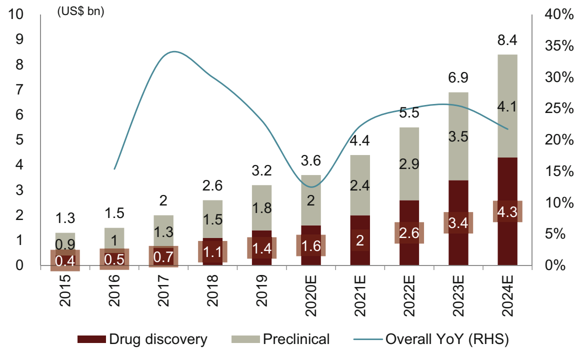


Fig. 5.8 China's market for drug delivery and clinical CRO services. *Source* Frost & Sullivan, CICC Research

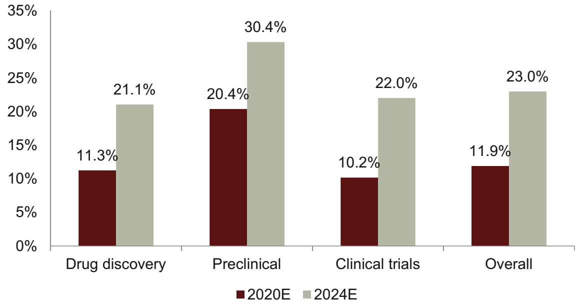


Fig. 5.9 China's share in global market for drug delivery and clinical CRO services. *Source* Frost & Sullivan, CICC Research

For production and supply, it is crucial to standardize and expand into high-value added businesses. Chinese pharmaceutical contract development and manufacturing organizations (CDMO) companies enjoy visible cost advantages over their foreign peers. In 2020, labor cost accounted for 12% of the total cost at domestic firm Asymchem, markedly lower than 35% at overseas industry giant Recipharm. This, coupled with high production efficiency, has enabled Chinese CMDOs to acquire more overseas orders, leading to an increase in China's share in the global CDMO market from 6% in 2011 to 8% in 2017.

Chinese companies used to focus on low-value-added and non-standard businesses, but are now gradually expanding into high-value-added business. Innovative drug manufacturing is a complex process that involves various components such as basic chemicals, starting materials, non-GMP intermediates, GMP intermediates, active pharmaceutical ingredients (API), and preparations, with the greatest added value occurring during the late-stage procedures. European and US CDMOs typically specialize in producing high-value-added products like API and preparations. Conversely, China lacked standardized production capacity in the past, and domestic companies mostly focused on the manufacturing of low-value added intermediates. After China joined the International Council for Harmonization of Technical

Requirements for Pharmaceuticals for Human Use (ICH), Chinese CDMO companies started to receive orders for phase III or commercial API and preparations from 2015 onwards, expanding into high-value added businesses.

5.2.2 Insights into Biotech Innovation in Agriculture

We think China's agriculture sector could primarily focus on incremental innovation while occasionally engaging in radical innovations. Given China's success in rice cultivation, we think favorable policies, governmental mechanisms, and cooperation between public and private sectors are conducive to biotech innovation in agriculture.

5.2.2.1 A Combination of Incremental Innovation and Radical Innovation

China's agriculture industry could mainly focus on incremental innovation, and radical innovation is more effective in some fields. We think innovation-driven technological upgrades in the agriculture sector may drive production efficiency. We believe incremental innovation is the dominant pattern for the agriculture sector. However, we suggest encouraging radical innovation in segments characterized by low return on investment (ROI) and great uncertainty.

In discussion of incremental innovation, seed production serves as a fitting example. Technological R&D in the seed production sector mainly focuses on insect-resistant and stress-tolerant traits which could help improve crop yields. Through hybrid technology, genetically modified seeds develop new stress-tolerant traits. From the evolution of breeding technology, we note that any new technology represents an innovation based on the previous technology.

The H7N9 avian influenza vaccine R&D serves as a prominent example of radical innovation (Fig. 5.10). In 2013, the H7N9 avian influenza virus started to spread in China, and by 2017, it had mutated into a highly pathogenic strain. During this period, the Ministry of Agricultural and Rural Affairs of China developed disease prevention and control strategies and collaborated with scientific research institutes such as the avian influenza reference laboratory of Harbin Veterinary Research Institute to develop vaccines. In 2014, a recombinant inactivated avian influenza virus vaccine (H7 subtype) was released. In 2017, an inactivated bivalent vaccine (H5 + H7) which could completely protect poultry from invasion of H5 and H7 virus subtypes was developed. Afterwards, the Ministry of Agricultural and Rural Affairs encouraged companies to produce and apply the vaccines. In the example above, the government plays a leading role in the early stage of vaccine R&D, while the innovation process shows more radical features.

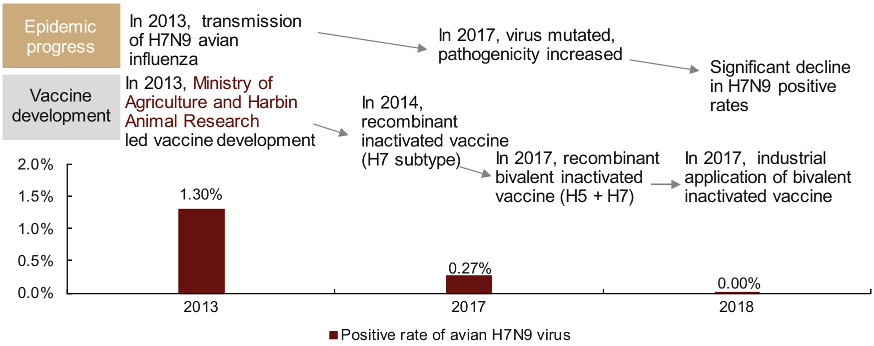


Fig. 5.10 Radical innovation of H7N9 vaccines in China. *Source* Ministry of Agricultural and Rural Affairs of China, CICC Research

5.2.2.2 Drivers of Biotech Innovation in the Agriculture Sector

Methods to incentivize biotech innovation in the agriculture sector include increasing market share and expanding new markets. During the process of incremental innovation, companies could obtain larger market shares by improving production efficiency. For instance, both Yuan Longping Hi-tech Agriculture (YLHA) and Monsanto Company enhanced their presence in the seed production market from the sales of new products. Similarly, Muyuan Foods enjoys cost advantages in the animal farming market from operations. In addition, small farms may exit the market amid the fierce competition. As for radical innovation, launches of new technology and products may open new markets.

R&D is the cornerstone, and accumulation of biotechnologies bolsters innovation. R&D serves as the foundation for both incremental and radical innovation. Through their exclusive R&D system and the technological advancements they acquire during the production process, companies enhance their products in response to customer feedback, resulting in incremental innovations.

Profits are gained through the excess returns formed through market competition and the positive externality of the industrial value chain. In terms of incremental innovation, we think high-quality seed varieties of a seed producer often enjoy higher prices and profit margin. For example, YLHA's earnings beat the sector average due to its advantages in rice varieties. In contrast, the returns from radical innovation are typically reflected at the public level, which has the potential to stimulate growth for the entire sector.

Companies' R&D investment fuels incremental innovation, whereas the government plays a leading role in supporting radical innovation. Funds for incremental innovation mainly come from companies' excess returns (from previous innovation) or financing proceeds, and funds for radical innovation mainly come from funds for national scientific research.

5.2.2.3 Insights from China's Biotech Innovation in Rice Breeding

China is the world leader in breeding hybrid rice, with its rice yield surpassing that of other countries. China's success in seed breeding proves that public–private cooperation is beneficial to the establishment of policies, governmental mechanisms, and a commercial system.

Large-scale cooperation mechanism bolsters innovation in the early stage. This was exemplified by Mr. YUAN Longping and his team, who discovered a male sterile rice crop known as "wild-abortive" (WA). Working with the China National Cooperative Hybrid Rice Research Group, which was established by over 30 agriculture-related government departments and companies, they researched three-line hybrid rice breeding technology. Due to their efforts, China cultivated the world's first three-line hybrid rice in 1973 and began to grow the crop in 1976. We note that large-scale cooperation resulted in the efficient use of manpower and resources, fueling research and application of hybrid rice breeding technology.

Intellectual property protection system lays a foundation for breeding innovation. *Regulations of The People's Republic of China on the Protection of New Varieties of Plants* was introduced in 1997 to protect the intellectual property rights of new plant varieties. Hybrid rice is one of the first 10 varieties listed. Since then, China has continued to strengthen its intellectual property rights protections for rice. In 2007, a DNA fingerprint detection method was introduced to prevent intellectual property infringement of rice varieties, and stricter infringement regulations were implemented compared to other crops. In 2020, the country pioneered an essentially derived varieties (EDV) protection system, bolstering original innovation protection in rice breeding. Overall, we think the strong efforts in the intellectual rights protection contributed to innovation in rice breeding.

The shift in roles between the government and companies empowers commercial seed breeding. We attribute the advanced commercialized rice seed breeding system to efficient cooperation between the government and private sector. First, the government launched favorable policies to encourage the exchange of scientific and technological resources, including human resources. For example, the Ministry of Agricultural and Rural Affairs called for a pilot reform aimed at guaranteeing the rights and interests relating to scientific research achievements in the seed sector in 2014, which accelerated the talent exchange between scientific institutions and seed breeding companies. Second, rice breeding companies continue to enhance competitiveness through M&As. For example, YLHA consolidated Hunan AVA Seeds Co., Ltd. in 2007 and acquired Golden Rice Seeds Co., Ltd. in 2016, enhancing its seed breeding strengths. In addition, the dominant role began to shift from the government to companies during the commercialization process. Among the hybrid rice varieties which applied for national approval, only 15% of them came from the private sector over 2001–2005, according to Ministry of Agriculture (MOA). However, the proportion rose to 91% in 2016–2020, showing that companies began to pursue innovation after the government paved the way for development. We think synergies between the government and companies are catalysts for growth in the rice seed breeding business.

5.3 Experience at Home and Abroad: The Government's Role in Promoting Biotech Innovation

From our perspective, the Chinese government can learn from overseas experience in stimulating biotech innovations. The US has set a good example for innovations in the pharmaceutical industry, with a diversified fundraising system, reasonable barriers to entry, and a friendly innovation environment. We also explore the potential room for China's agriculture sector to promote biotech innovation, based on our analysis of legislation, mechanisms, and R&D systems in China and other countries.

5.3.1 Innovation in Pharmaceutical Industry: Experience in the US

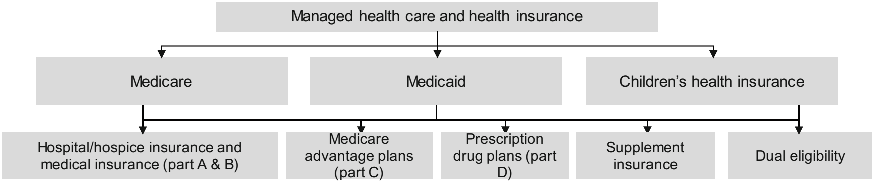
The boom in the biotech and pharmaceutical industry in the US was closely related to reforms of the pharmaceutical market system. Since the twenty-first century, pharmaceutical reforms have been introduced to offer a guarantee for pharmaceutical companies to benefit from their innovations, thereby encouraging continued investment in drug R&D. This has paved the way for building a competitive market for biotech and pharmaceutical manufacturing.

While the US pharmaceutical market rapidly thrived on the emergence of large numbers of industry giants, it was gradually monopolized by large players, leading to high prices for new drugs. Demand to reduce new drug prices and enhance affordability has been growing in the US in the past few years, and pharma companies such as EQRx aiming to provide more affordable new drugs began to emerge.

Although the US pharmaceutical industry is far from perfect, we believe China can learn from its effective incentives for innovation.

The first measure is to improve the payment system. The US has built a diversified fundraising system and encouraged more payment methods for innovative drugs. Government-led healthcare insurance mainly covers disadvantaged groups in the US. In the US, pharmaceuticals are mainly paid for by government-led basic healthcare insurance, which targets the elderly, children, and the disabled, and accounted for almost 50% of pharmaceutical payments in 2018 (Fig. 5.11). On the other hand, commercial insurance covers over 60% of the employed population and accounted for 39% of pharmaceutical payments in the same year. Individuals are responsible for paying the remaining medical costs as out-of-pocket expenditures. We believe the diversified insurance system in the US can satisfy the needs of different groups of patients, and maximizes payment capability.

Negotiated pricing is the basic pricing principle in the US pharmaceutical market, but the actual pricing is not transparent due to the involvement of different interested parties. Government-run insurance programs Medicare and Medicaid are the largest payers in the US pharmaceutical market, and their pricing policy is an important



Content	Provider	Funder	Sources of financing	Coverage
Hospital/hospice insurance (part A)	Government	Government, NGO, commercial insurance companies, health care organizations	Payroll tax	Inpatient care, home health care, hospice care, skilled nursing facility care
Medical insurance (part B)	Private groups		US Treasury revenue, premiums paid	Outpatient, inpatient, medical care, limited outpatient prescription drugs
Medicare advantage plans (part C)			Premiums paid	Prescription drugs, dental and vision insurance, wellness programs
Prescription drug plans (part D)				Cost of prescription drugs
Supplement insurance (Medigap)				Extra coverage
Dual eligibility				Both Medicare and Medicaid benefits

Fig. 5.11 US basic healthcare insurance system. *Source* CMS, CICC Research

reference for commercial insurance companies. Medicare Part D requires government bodies to delegate price negotiation with pharmaceutical firms to third-party pharmacy benefit managers (PBM), but the payments and refunds between all parties are not disclosed, leading to potential implicit costs.

The second measure is to make barriers to entry reasonable. For example, the US has a higher standard for pharmaceutical innovation, but lower regulatory costs. The FDA has gradually set a high standard for new drug approval in the past two decades, strictly restricting the marketing of medicines with unclear clinical significance. Such efforts helped avoid low-quality R&D investment. The US launched a reform of its pharmaceutical patent system in the 1980s, which prolonged the exclusive patent protection for new drugs and enhanced the bargaining power of large pharma companies. According to IQVIA, generic drugs accounted for around 90% of prescription volume in the US, but only 20% of total pharmaceutical sales value in 2020. This supply–demand structure motivated pharmaceutical companies to continue to invest in the R&D of differentiated innovative drugs.

Looking back at China's reforms of its pharmaceutical approval system since 2015, we believe domestic regulators have learned from the successful experience of overseas regulators such as the FDA. China's innovative drug industry started to thrive. After joining the ICH in 2017, China has been adapting the R&D, registration, manufacturing, and regulation of drugs to international standards.

The third measure is to enhance the innovation environment. As suggested by US experience, this might include the development of basic research, the search for scientific innovations with no specific commercial objectives, and an efficient capital market for the pharmaceutical sector, and also a coordinated fund management system to ensure efficient use of funds for basic research. The public sector is an important source of funding for basic research. Developed countries generally have an independent management system for R&D funds from the public sector.

A mature system for IP protection facilitates commercialization of R&D results. The US Bayh-Dole Act adopted in 1980 gives researchers rights to intellectual property (IP) generated from federal funding, thus incentivizing academic institutions and researchers to innovate.

An efficient capital market is also important. New drug R&D entails multiple procedures, requires extensive investment, and is often high-risk. This makes venture capital important for the development of biotech sector. The US has ample professional biotech investors, and a relatively mature valuation system. The capital market can share the risk of failed innovation. In addition, secondary markets such as NASDAQ provide a low-cost exit channel for venture capital and equity investors.

5.3.2 Agricultural Innovations: A Global Perspective

We discuss the potential of China's agriculture sector to promote biotech innovation based on our analysis of legislation, mechanisms, and R&D systems in China and other countries. We propose that legislation that prioritizes intellectual property rights may incentivize companies to innovate. Additionally, effective governmental mechanisms can provide critical support for innovation, and balanced public–private relationships in R&D can further enhance sustainable innovation.

5.3.2.1 Legislation for Protection of Intellectual Property Rights

In order to encourage biotech innovation in the seed business, China has been stepping up efforts to enhance legal protection over intellectual property rights. In 1997, it granted intellectual property rights to developers of new plant varieties through the *Regulations of The People's Republic of China on the Protection of New Varieties of Plants*. In 2000, *the Seed Law of the People's Republic of China* included general provisions on the protection of intellectual rights for new plant variety developers. In 2005, the amendment to the *Seed Law* standardized the protection for new plant variety developers. In 2015, the *Seed Law* was revised for the second time, proposing the approval of applications for main crop varieties and the registration for other crops. In addition, the revised version strengthened efforts in intellectual rights protection and encouraged innovation. We think China is improving its intellectual rights protection laws for the seed sector, which will likely promote sustainable innovation.

5.3.2.2 Innovation-Oriented Mechanisms

Seed certification, germplasm protection and utilization, and land transfer are three effective ways to stimulate biotech innovations in agriculture.

First, the seed certification system guides market-oriented seed breeding. However, China currently adopts a different seed certification system from that of other countries. This leads to lower yields and traits of some seeds in China, including corn and soybean for feed use, compared to other countries. According to FAO, China's corn and soybean yields in 2019 were 6.3 tonne/ha and 1.9 tonne/ha, lagging far behind the US, Canada, and Argentina, among others. We believe this is caused by the differences in seed certification systems. In contrast, companies in the US select high-quality seeds independently and send them to certification institutions for professional tests and reports. We believe this system allows companies to develop seeds with better traits in a competitive market. In contrast, China's seed certification work is headed by the government. Although seed quality is secured, competition in the seed market is relatively inadequate. Under this system, we may see few breakthroughs in seed quality.

A complete certification system could bolster biotech innovation in the seed market. Leaders in the global seed sector developed their seed certification systems at an early stage. For example, the US developed and optimized its seed certification system in the 1950s, and Argentina established its system in 1978. After years of development, these countries now enjoy relatively comprehensive certification systems. Companies send their seeds for certification independently and consumers make choices between different seed products in these countries, which bodes well for market competition and sector improvement, in our view. After the establishment of its seed certification system in the 1950s, the US saw rapid growth of its Seed Cost Index. We think this also reflects the improving quality of seeds. In addition, data from California shows that the planting area of certified rice seeds is positively correlated with the rise of rice yields in the state. We contend that the seed certification system offers farmers high-quality seeds, enhances their earnings growth, and inspires them to continue to sow high-quality seeds, thus fostering innovation in the seed production sector.

China continues to explore and simplify its seed certification procedure to encourage market-oriented business operation. The previous certification system had been in place for a long time, contributing to the development of the seed sector. The *Seed Law* passed in 2016 proposed a simplification of the certification procedure and increased test channels. According to the big data platform for seed varieties, the number of rice seed varieties certificated rose from 27 in 1978 to more than 1,913 in 2020 as a result. Data from Ministry of Agriculture and Rural Affairs of China shows that the number of hybrid rice varieties involving a planting area of more than 6,666 hectares has dropped in recent years, reflecting the low acceptance from the market and weak quality advantages of new varieties.

Second, systematic germplasm protection and utilization support biotech innovation. Germplasm protection refers to the collection, detection, and reserve of valuable crop genes, while germplasm distribution aims to cultivate varieties with better traits by crossing valuable germplasm with modern germplasm. China has rich germplasm resources, but needs to enhance utilization and protection. China has 520,000 germplasm reserves as of 2020 (only second to the US), as announced at the 2021 Work Conference on Crop Germplasm Resources Protection and Utilization. But the germplasm utilization rate in China is relatively low. In 2020, only 21.2% of the germplasm reserves were distributed to companies and research institutions in China (vs. 41.6% in the US and 55.4% in Japan). In addition, we expect China to step up efforts in germplasm protection. Germplasm resources for main grain seeds in China dropped 72% from 11,590 in 1956 to 3,271 in 2014. Among germplasm reserves in China, only 7% are imported (vs. 62% in the US). We think China still has much work to do in terms of germplasm protection and utilization, and this weakness impedes China from enhancing germplasm diversity or innovation to some extent.

The germplasm protection mechanism empowers seed breeding and innovation. Developed countries have committed considerable effort to protecting germplasm, and have established related mechanisms. The US started to establish its germplasm bank in 1862 and continued to search for new resources at home and abroad. We calculate the correlation between germplasm reserves and grain yields at 0.87. This means that the increase in germplasm reserves could support seed breeding. China began its protection work in the 1980s and lacked experience in establishing a national germplasm bank. At present, China is strengthening its germplasm resource protection and utilization, and formulates systematic solutions correspondingly after launching food security-related policies. We think this bodes well for China's innovation in the seed production sector.

A systematic sow registration mechanism is conducive to breeding, and China has to catch up with overseas peers. The US, Denmark, and Canada have bigger gene banks for hog and poultry breeding than most countries in the world. They have systematic sow registration mechanisms, which include procedures such as the establishment of national sow registration associations, sow quality measurement and evaluation, hog data collection and registration, database establishment, and genetic mapping and gene analysis for breeding. The US and France have registered more than 80% of their sows, whereas China has registered only 16.7%.[2] We believe this has hindered China's improvement in gene databases and genetic map analysis for breeding, negatively impacting sow fertility. Nonetheless, we acknowledge that the country is making efforts to improve in this area.

Third, land transfer system enables innovation in the cropping value chain. China promotes land transfer as a solution for the fragmentation of arable land. Changes to the land transfer system have created larger farms and rationalized farms, creating economies of scale that have fueled technological innovation in agriculture. China's farming sector is dominated by small farms, and features a low per capita farming area. Fragmented arable land further weighs on cultivation efficiency. In 2014, the country deepened its land reforms, separated land management rights from land

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[2] Li, Y., Liu, Z., Liu, J., et al. (2013). The World's Pig Breeding System and Its Implication on China, (6), pp. 52–54.

ownership rights and contracting rights, and encouraged the transfer of land management rights. In 2020, the confirmation and registration of contractual management rights for rural land was largely completed, and management rights were transferred for over 40% of contracted farmland.

The efficient implementation of the land transfer system enables agricultural innovation. At present, modern technologies can reduce costs and improve efficiency for large-scale planting. We think large-scale planting backed by the land transfer system could also enhance the overall competitiveness of the cropping sector, and bolster the application of new agricultural technologies and further innovation in the sector. We expect to see obvious positive results in the medium to long term.

5.3.2.3 A Balanced Public–Private Relationship in R&D

Commercial seed breeding systems are mature in other countries, while more time is needed for China's efforts to pay off. A well-established commercial seed breeding system facilitates exchange of resources between scientific institutions and companies, which is essential for innovation in the seed production sector. Major seed producers have enjoyed mature seed breeding systems, while China has not seen results due to its late entry in this area. The proportion of commercial projects in total new variety application projects exceeds 95% in the US, France, and Germany. The figure is 55% in China, indicating that China has room to develop its commercial seed breeding system. Additionally, the approval rate of new varieties for commercial breeding exceeds 70% in the US, France, and Germany, compared to just 41% in China. Thus, Chinese companies must improve the quality of their commercial project varieties and increase their efforts in innovation to enhance the approval ratio.

Government's role is crucial in the optimization of commercial seed breeding system. The success of the US, with the introduction of the Federal Technology Transfer Act of 1986, is a good example. This act facilitated the exchange of talent and resources between scientific institutions and companies, and established a mechanism for profit distribution, thus empowering cooperation between the two entities. Meanwhile, the US government gradually shifted its focus from seed production to research so that companies could apply new technologies independently. Thanks to its efforts, the business scale of US companies has increased. According to the USDA, the number of US seed producers reached 329, up 22% from the level in 1982 when the commercial seed breeding system was primarily established in the US. In addition, the number of companies operating breeding businesses increased for all crop varieties, showing the rapid development of the commercial seed breeding in the US.

When discussing public–private cooperation, we expect to see synergies between China's public and private sectors and expect companies to become more powerful in the market. The State Council proposed in 2011 the establishment of a modern seed sector with companies playing the leading role. China has stepped up efforts to strengthen intellectual property rights protection and judicial supervision for the seed sector so as to encourage companies to invest in seed breeding R&D. According to

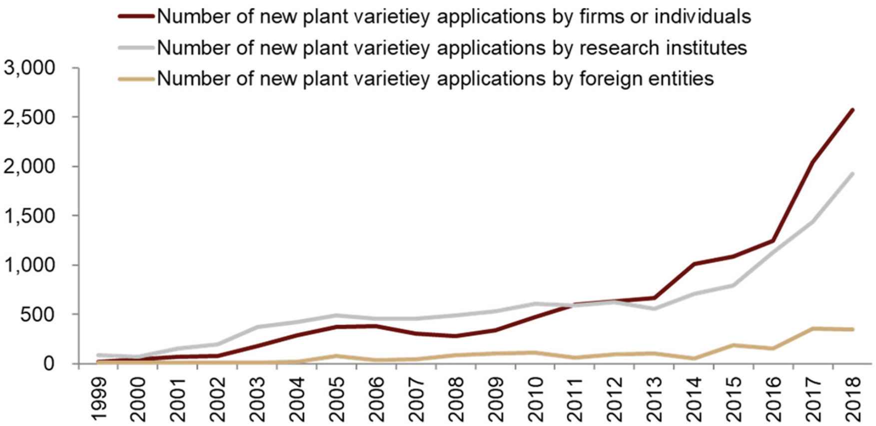

Fig. 5.12 Application for new plant varieties from companies, individuals, and scientific institutions in China. *Source* Report on China's agricultural intellectual property index, China Center for Intellectual Property in Agriculture, 2016; China Statistical Yearbook on Science and Technology, National Bureau of Statistics of China, 2016–2019; CICC Research

China Statistical Yearbook on Science and Technology 2019, there were more companies and individuals applying for new plant variety projects than scientific institutions in 2011, and the proportion of companies and scientific institutions reached 53% and 40% in 2018 (Fig. 5.12). Despite this progress, overlaps in work between public and private sectors are still observed. Hence, it is essential for China to improve its public–private cooperation in seed breeding R&D.

Chapter 6
Smart Manufacturing

Abstract The smart manufacturing industry stems from the manufacturing and logistics industries, which is crucial to the formation and sustainability of an innovation economy. The manufacturing sector can support innovation activities, promote the industrialization of innovative products and services, and propel the innovation cycle. Furthermore, development of the logistics sector can significantly boost trade by lowering transportation costs, and can support complex supply chains. In addition, the logistics industry's digital transition may have accelerated during the COVID-19 pandemic, and logistics plays a key role in supporting innovation in the digital economy.

China's manufacturing industry has developed rapidly since the 1990s, and its innovation capability has improved significantly. However, Chinese manufacturing companies are less active in pursuing innovation, as evidenced by their output and their revenue from innovative products. Reasons behind the weaker innovation include insufficient R&D investment, fragmented investment structure, and mismatch between R&D and production as well as between production and application. We also see deeper reasons for weaker innovation capability. China's manufacturing industry is export-oriented. The emphasis that companies place on capacity expansion also weighs on the innovation capability of the manufacturing industry.

We also examine the cost efficiency of domestic logistics, and find that while China has low logistics costs, efficiency could be improved. First, China is able to achieve low logistics costs at the expense of profit margin. Second, China's labor efficiency remains relatively low. We attribute the low efficiency of China's corporate logistics businesses to three factors: Low automation rate, low transport efficiency, and a lack of integrated transportation. Furthermore, China is not a strong player in international logistics, which limits its ability to build reliable supply chains.

Innovations in digital technologies present new opportunities for China's smart manufacturing industry. For the manufacturing sector, we expect more engineering-based innovation and business model-related innovation to emerge in China given there is a new round of technological revolution and industrial transformation in the making with the integration of the digital economy and the manufacturing industry, and a possible flattening of the smile curve. The logistics sector may benefit from a large domestic market with stronger economies of scale, and technology could play

CICC Research, CICC Global Institute, *The Rise of China's Innovation Economy*,
https://doi.org/10.1007/978-981-99-8231-8_6

a greater role here. We think logistics companies' increasing R&D expenses and China's leading 5G and AI technologies may help the country catch up in the area of logistics. There is also opportunity for China to develop its international logistics system as the competitive landscape of international logistics may evolve.

6.1 Manufacturing and Logistics are Essential for Innovation

Both the manufacturing and logistics sectors are essential for technological innovation. Manufacturing can support innovation activities, promote the industrialization of innovative products and services, and propel the innovation cycle. Logistics can boost trade by lowering transportation costs, and can support complex supply chains. Digital transition in the logistics industry is accelerating, and the development of logistics can in turn support innovation in the digital economy.

6.1.1 The Manufacturing Sector is the Engine for Innovation Activities

Manufacturing has three notable characteristics—intensive factor inputs, complex production processes, and economies of scale. As such, the manufacturing sector is the key facilitator of innovation activities, placing it in a position to contribute to industrial applications of innovative products and services, and is one of the sectors that is most active in pursuing innovation. The total factor productivity (TFP) growth rate of the manufacturing industry is higher than that of other sectors.[1] The manufacturing sector's rapid technological advances make it a main engine of innovation, in our view.

Manufacturing is vital to innovation activities, in our opinion, as it underpins technological breakthroughs in semiconductors, biopharmaceuticals, and other high-tech industries. It also helps improve the performance of machinery, instrumentation, and other equipment, and is crucial to each step of the product innovation process, such as the inception of an innovative idea, trial production, and mass production.

The complexity of manufacturing processes means the sector may present more innovation opportunities than other industries. Experience in highly complicated manufacturing processes can help improve techniques and technologies, thereby facilitating innovation. A large manufacturing system, in our view, is the foundation of innovation.

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[1] Jia, F., Ma, X., Xu, X., Xie, L., et al. (2020). The differential role of manufacturing and non-manufacturing TFP growth in economic growth.

Samaniego, R. M., Sun, J. Y. (2016). Productivity growth and structural transformation.

Ilyina, A., Samaniego, R. (2012). Structural change and financing constraints.

Products of the manufacturing industry underpin innovation in other industries. Advanced equipment, laboratory instruments, and other key devices are crucial to innovation in all industries. They are the basic resources and the impetus for innovation. The machinery, instrumentation, and electronics manufacturing sectors contribute more to innovation than other sectors of the manufacturing industry, and they play an essential role in spurring innovation.[2]

Economies of scale in manufacturing can help reduce cost and spur innovation. For example, we estimate that a 100% increase in the installed capacity of photovoltaic (PV) units can reduce the cost of such units by around 13%, and a 100% rise in the installed capacity of wind power units can cut the cost of such units by about 7%. Lower costs will help companies rapidly upgrade alternative energy technologies, in our view.

Economies of scale help shape innovation clusters, enabling knowledge spillover. We think the process of shaping industrial clusters will create synergies between industries, make network-externality-based knowledge spillover possible, and spur innovation. Silicon Valley, Tokyo, and Shenzhen are typical innovation clusters (Fig. 6.1).

The manufacturing sector drives the innovation-application-investment cycle as this sector can convert innovations into economic returns, and provide capital for additional innovation activities. High capital intensity in manufacturing, which represents productive investment, can contribute to a high savings ratio. It can also lay a foundation for economic growth and innovation in developing countries, particularly in East Asia.[3]

Manufacturing helps improve labor productivity, and stimulates innovation. This sector can not only create jobs for surplus labor in the agriculture industry, for example, but also stimulate the migration of labor from low-productivity sectors to high-productivity sectors, in our view. Manufacturing companies, via innovation, can improve labor productivity and create competitive advantages. As such, we believe innovation is vital to the growth of manufacturing companies.

6.1.2 Logistics is Vital for Technological Innovation

Logistics supports commodity trade, and facilitates production and circulation. In the digital economy, the penetration of new technologies into various logistics processes is accelerating, and improvements in logistics quality and efficiency support the efficient circulation of goods and information. As a result, we think logistics is closely linked to technological innovation. In this section, we explain why the development of the logistics industry is vital for technological innovation from three aspects.

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[2] Pisano, G., Shih, W. (2014). Producing prosperity: Why America needs a manufacturing renaissance.

[3] Szirmai, A. (2012). Industrialisation as an engine of growth in developing countries, 1950–2005.

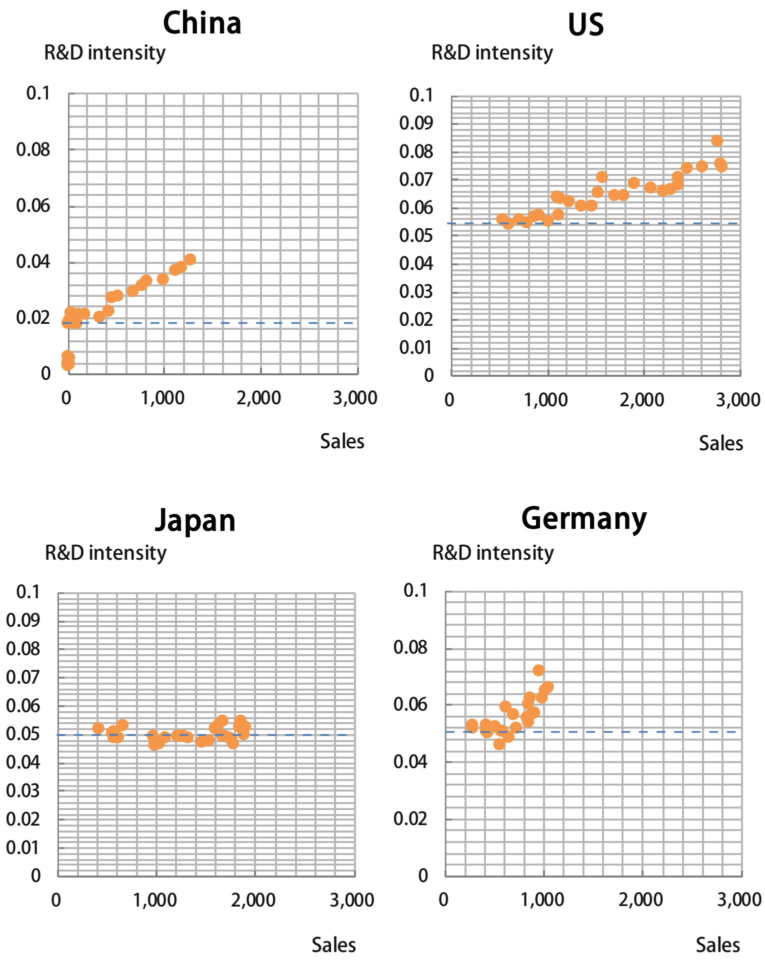

Fig. 6.1 Big firms tend to have higher R&D investment intensity than smaller firms (unit: US$1bn). *Note* We use data for top 200 technology-intensive manufacturing companies in China, the US, Japan, and Germany over 1993–2020. *Source* Bloomberg, CICC Global Institute, CICC Research

6.1.2.1 Development of Logistics Industry Facilitates the Circulation of Productive Factors

Logistics links manufacturing and consumption, thus boosting the circulation of productive factors. Manufacturing is characterized by more efficient division of labor and large-scale production. However, consumption is fragmented and diverse. As the mismatch between manufacturing and consumption creates demand for logistics, logistics closely links manufacturing and consumption, creating value from the movement of productive factors. Logistics is also the link between key processes in industrial goods production. Raw material logistics, production logistics, finished

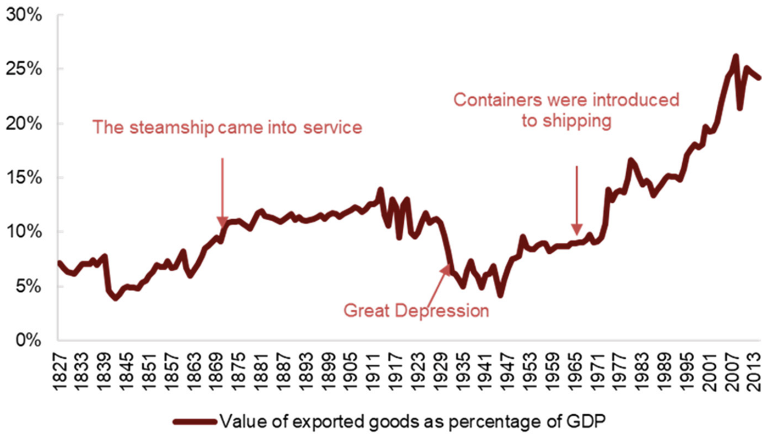

Fig. 6.2 Value of exported goods as a percentage of GDP is rising. *Source* WTO, CICC Research

goods logistics, and distribution logistics link raw material procurement, manufacturing, goods distribution, and consumption. As a result, logistics accounts for more than 90% of the time in manufacturing and sales. Its efficiency thus determines the efficiency of the circulation of productive factors.

Circulation costs fall rapidly with the advancement of logistics. For example, the introduction of shipping containers in 1966 significantly improved logistics efficiency and reduced logistics costs. Loading efficiency of US freighters increased from 1.7t/hour to 30t/hour, and loading and unloading costs fell to around US$0.16/t from US$5.8/t.[4]

Shipping rates have remained low in absolute terms for years with improvements in shipbuilding technology (shipping accounts for over 80% of global freight volume). Thanks to upgrades in shipbuilding technology, vessels have become larger with higher carrying capacities, leading to lower unit shipping cost. In 2020, the average capacity of dry bulk carriers was 2.4 × the level in 1970, according to Clarkson, and the unit shipping cost of a 170,000t vessel was just 60% of that of a 70,000t vessel in 1970, according to Maritime Economics. In absolute terms, the average annual freight rates of dry bulk carriers and containers have stayed low.

Falling global logistics costs facilitate global trade and goods circulation. According to the World Trade Organization (WTO), the value of exported goods as a percentage of GDP rose to 24% in 2011 from around 7% in 1966 after containers were introduced to shipping (Fig. 6.2).

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[4] Kneller, R., Bernhofen, D., El-Sahli, Z. (2015). Estimating the effects of the container revolution on world trade.

6.1.2.2 Logistics Plays a Great Role Amid Technological Innovations and Industrial Upgrades

More complex supply chains impose higher requirements on logistics. According to Wind, the proportion of labor-intensive industries in the domestic manufacturing industry fell by 7.8 ppt to 22.8% over 1999–2020, capital-intensive industries grew by 5.8 ppt to 40.0%, and technology-intensive industries increased by 2 ppt to 37.3%. Specifically, the structure of manufacturing value added is changing, with computer communication and electronic equipment seeing a 0.19 ppt increase in their annualized share and the automobile industry recording a 0.17 ppt rise in its share.

Supply chains are becoming more complex amid industrial upgrades. As vehicle and electronic communication device manufacturing involves complex production techniques and multiple types of raw materials (a vehicle has around 20,000 parts), managing their supply chains is more complex and difficult. Therefore, we think supply chain logistics should upgrade along with industrial upgrades. Meanwhile, the demand for real-time logistics in the supply chain is increasing. For example, in the US from 1970 to 1980, airfreight of high-value-added products amid industrial upgrades boosted FedEx's business (FedEx's air package volume rose at a CAGR of 35% over 1977–1988) according to FedEx historical data.

The reduction in costs and improvements in efficiency in the manufacturing industry are driving upgrades in the logistics industry. According to the National Bureau of Statistics (NBS), profits of Chinese industrial companies were under pressure in the past decade, with profit margin falling by 1.1 ppt from 2010 to 6.2% in 2019 (Fig. 6.3). However, we expect third-party logistics to help companies lower costs and improve efficiency through supply chain management. According to the European Commission, companies expect supply chain logistics to help increase production efficiency by 10%, shorten production time by 25–35%, and reduce total cost by 10%.

6.1.2.3 Logistics Requires Further Post-Pandemic Digitalization; Transition from Just-In-Time (JIT) to Just-In-Case (JIC) Creates Greater Need for Flexibility

As the global supply chain was hit hard by the COVID-19 pandemic, we expect the development of digital logistics to accelerate, and the flexible deployment and dispatching of supply chain logistics are likely to receive more attention.

COVID-19 has accelerated the development of digital logistics. Demand for contactless delivery has surged due to COVID-19, and we see sizable growth potential in unmanned application scenarios or scenarios with less human involvement. As demand for contactless delivery grows, the demand for intelligent logistics technology will likely increase, raising requirements for its application and reliability. For example, the delivery of goods and materials by unmanned vehicles played a vital role in combating the COVID-19 resurgence in Guangzhou in June 2021.

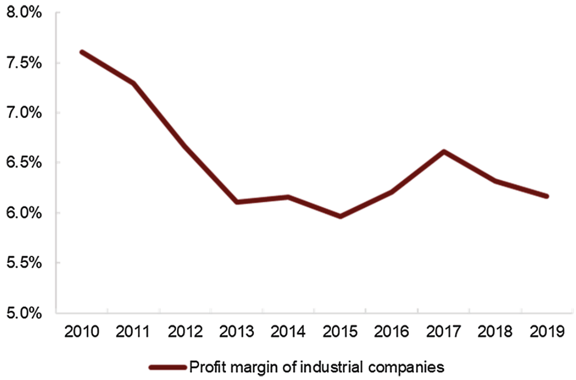

Fig. 6.3 Industrial companies' profit margins have been under pressure in recent years. *Source* Wind, CICC Research

Development of digital logistics will continue to accelerate. A survey on the impact of COVID-19 on supply chain logistics in 2020[5] found that 64% of companies plan to speed up digital supply chain transformation after COVID-19 subsides, and 58% plan to accelerate the coordinated construction of end-to-end supply chains. We expect an increasing number of companies to use digital logistics management platforms to respond quickly to changes in transportation status, making it transparent and controllable.

From JIT to JIC, flexible deployment and dispatching of logistics has strengthened. After COVID-19 disrupted supply chains, we expect the following changes in the logistics industry. First, a transition from JIT to JIC. Logistics efficiency and costs will no longer be the priority, and adaptability will become more critical as it would allow companies to respond better to emergencies. Second, supply chains will be more localized and fragmented. As revealed by the survey mentioned in the previous paragraph,[6] more than half of the companies surveyed stated that they would optimize regional supplier distribution and prepare more suppliers for key products.

We think logistics companies need smarter and more compatible operation systems to address strategic redundancy and a fragmented supply chain, thus allowing logistics centers to be more compatible with multiple businesses and responsive to emergencies. Furthermore, deployment and dispatch will be more convenient, and logistics capacity can be replenished or expanded quickly.

Looking ahead, the development of logistics is likely to encourage technological innovation in the digital economy. We expect logistics to accelerate production, goods turnover, and product upgrades in the upstream industries, supporting manufacturing and product innovation. Meanwhile, logistics can meet the diverse needs of

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[5] Wang, Z. (2020). COVID-19's impact on companies' supply chain logistics construction, Logistics technology and application, 25(4).

[6] Wang, Z. (2020). COVID-19's impact on companies' supply chain logistics construction, Logistics technology and application, 25(4).

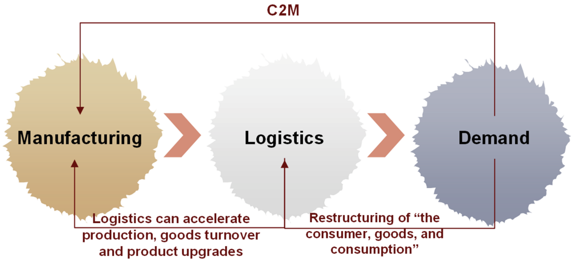

Fig. 6.4 Logistics links manufacturing and consumption; manufacturing and consumption are being upgraded. *Source* CICC Research

consumers via highly efficient parcel collection and delivery, and support consumption innovation by restructuring the three factors in consumption: Consumers, goods, and consumption scenarios (Fig. 6.4).

6.2 Global Experience in Smart Manufacturing and Supply Chain

We provide examples to discuss the possible ways of encouraging and utilizing technological innovations in manufacturing and logistics sectors. For example, the US government has played a key role in manufacturing innovation in the country, while Shein, an emerging Chinese fashion retail brand, has been able to expand its business efficiently by building up a smart supply chain.

6.2.1 The Path of Manufacturing Innovation in the US

The US has taken the lead in innovation, as demonstrated by its many achievements that are of great global significance. The value added of the US manufacturing sector represented about 25% of the total value added of manufacturing globally over 1970–2000. Leading information and communications technology (ICT) companies that emerged in Silicon Valley in the 1990s, e.g., Apple, Cisco, IBM, Intel, and Microsoft, accounted for about 66.7% of the global hardware, software, and service market.[7] In 2020, 10 of the top 20 companies in the global biopharmaceutical market are US companies, according to Pharmaceutical Executive.

Government has played a key role in making the US one of the world's most innovative countries. For example, the Defense Advanced Research Projects Agency (DARPA) has funded many R&D programs related to the internet, computer chips,

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[7] Kraemer, K. L., Dedrick, J. (1998). Globalization and increasing returns: Implications for the US computer industry. Information Systems Research, 9(4), 303–322.

self-driving vehicles, and global positioning system (GPS) technologies since its establishment in 1958.[8] This agency has played a crucial role in helping the US maintain its competitive advantage in technology. Key to DARPA's success in spurring innovation is the use of public funds to conduct venture investment and to steer strategically important R&D projects with high uncertainty and that attract little private sector investment.

The US government also plays an important role in facilitating the commercial use of innovative products and services. US government agencies directly fund companies' R&D projects.[9] Government procurement is crucial to the commercial use of innovative products and services in the early years of such products and services. The US government also introduced the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs to stimulate innovation among small- and medium-sized enterprises (SMEs).

Furthermore, the US government has helped create an innovation-friendly environment. For example, the government has created an innovation ecosystem consisting of companies, universities, research institutions, and consumers; has built a technology transfer system to facilitate the commercial use of innovative products and services; and uses tax incentives to stimulate innovation.

The US government has recently encouraged companies to relocate their production bases to the US to stimulate innovation. In 2019, the value added of the US manufacturing industry as a percentage of the country's GDP dropped to 11% from 16% in 2000 as the US's share of the global manufacturing industry declined to 17% from 26% in 2000.[10] The US has encouraged manufacturing companies to return to the country since 2010. The Biden administration plans to raise the minimum US content for manufactured goods purchased by the federal government from 55 to 60%, and then to 75% in 2029.

6.2.2 Shein: An Emerging Fashion Retail Brand Supported by Smart Supply Chain in China

Founded in China, Shein is a cross-border business-to-consumer (B2C) e-commerce platform that integrates design, production, and sales. The firm, which primarily sells clothing, has a high turnover ratio, and offers quick delivery as well as good value for money. It has entered international markets with a cross-border e-commerce platform. Shein also has a well-built manufacturing supply chain in China. We think its successful operating model is supported by its intelligent supply chain logistics system.

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[8] Van Atta, R., Windham, P. (2020). The Darpa Model for Transformative Technologies.

[9] Source: US National Science Foundation.

[10] Source: US Bureau of Economic Analysis, UNCTAD.

Shein's intelligent supply chain logistics system supports its "small order + repurchase" model. From the sales end, the company's monitoring of data on its independently built e-commerce channel enables it to respond more quickly to demand. From the production end, it prefers to cooperate with small and medium-size factories and rarely defaults on the payment for goods. It also provides financial support to suppliers, allowing them to purchase more equipment, and helps them introduce automation equipment to manage the production of multiple SKUs and products with various types of fabrics and sizes. Shein has also strengthened its control over suppliers. Suppliers must connect to its self-built supply-chain information system, allowing the company to conduct full-process data analysis of production and sales.

Shein has adopted a real-time monitoring system for domestic and overseas inventories. Its inventory management system is also connected to the upstream production system, allowing the company to control inventory replenishment and minimize inventory pressure. It also has intelligent cross-border delivery logistics. Shein digitalizes logistics information and uses big data algorithms to calculate delivery routes, thereby improving logistics efficiency.

China's manufacturing has gained an advantage in production capacity, with increasing interaction between R&D and manufacturing activities (and between manufacturing and consumer activities). Technological innovations may also benefit the logistics sector by lowering logistics costs and improving efficiency. In the next section, we evaluate China's manufacturing innovation and analyze the Chinese logistics industry's cost efficiency and value chain security.

6.3 Development of Manufacturing and Logistics Sectors in China

China is becoming increasingly important in the global manufacturing and logistics industries. Nevertheless, technological innovations in China's manufacturing industry remain insufficient, and the cost efficiency of China's corporate logistics businesses still needs to be improved. We analyze the reasons behind such deficiencies.

6.3.1 Status Quo and Challenges of China's Manufacturing Sector

China's manufacturing sector has developed rapidly since the 1990s. China represented 2.5% of the output of the global manufacturing industry in 1990, ranking No. 8. The percentage reached 6.5% in 2000 and 18% in 2010, with China ranking No. 4 and No. 1 in contribution to the global manufacturing industry. In 2019, China accounted

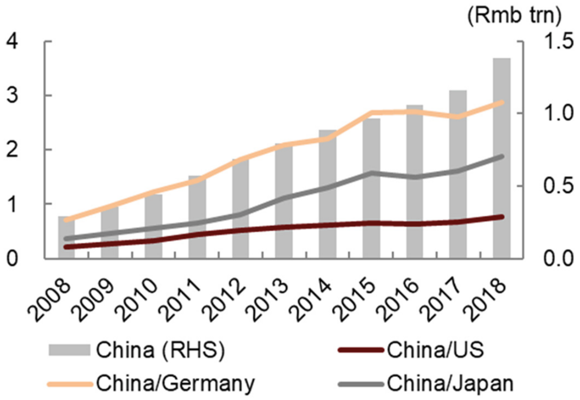

Fig. 6.5 R&D expenses have increased markedly in China's manufacturing sector. *Source* OECD, CICC Global Institute, CICC Research

for 29% of the output of the global manufacturing industry, notably exceeding the percentages for other countries.[11]

The R&D expenses of China's manufacturing sector have increased since 1990, exceeding that of Germany and Japan (Fig. 6.5). Meanwhile, China's manufacturing industry chain continues to improve, with companies launching novel products and rolling out new designs.

Nevertheless, technological innovations in China's manufacturing industry remain insufficient. First, the capability of China's manufacturing sector to innovate is relatively weak. The manufacturing sector consists of multiple subsectors that rely on different factors and production processes. Innovation capability of manufacturing subsectors varies.

Second, China's manufacturing industry is less active in pursuing innovation. The 2018 OECD Oslo Manual defines two types of innovation in manufacturing: Product innovation (including significant and gradual improvements in products) and process innovation (this includes innovation in production processes, organization, and management).

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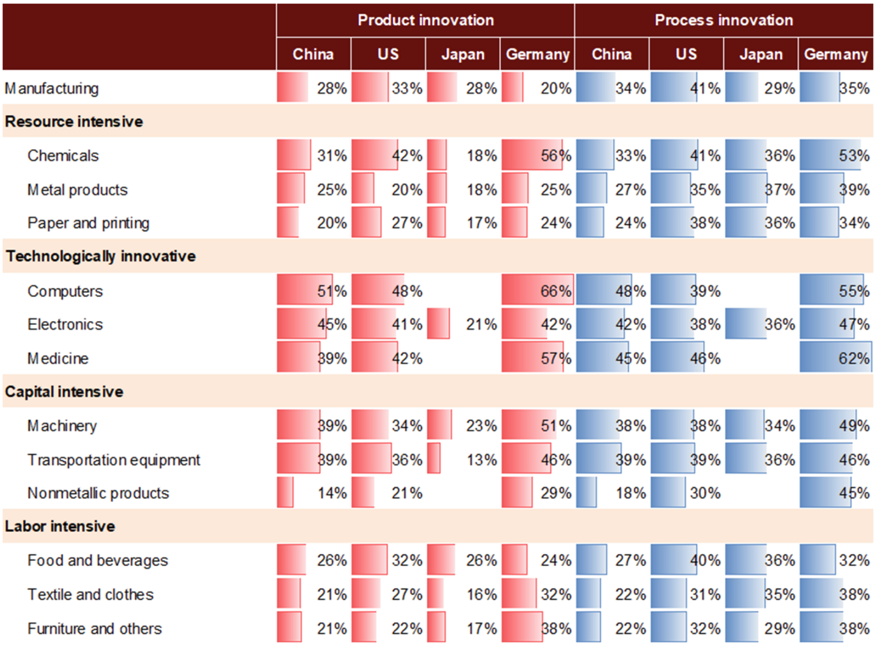
[11] Source: UNCTAD.

Data from NSF and the China Statistical Yearbook on Science and Technology shows that the percentages of Chinese manufacturing companies conducting product innovation and process innovation are 5 ppt and 7 ppt lower than that of their counterparts in the US. Specifically, the percentages of Chinese chemical companies innovating in products and processes are both more than 8 ppt lower than that of their US counterparts (Fig. 6.6).

Third, China's innovation-related output is lower than that of the US, Japan, and Germany. Companies developing new products account for 2% of the total number of manufacturing companies in China (vs. more than 10% in the US, Japan, and Germany). Novel products contribute 1% of revenue at Chinese manufacturing companies (vs. around 5% in the US, Japan, and Germany).

Overall, we think that insufficient R&D investment as well as deficiencies in the system encompassing R&D, production, and application of new technologies have hindered innovation in China's manufacturing industry. First, R&D investment in China is insufficient. OECD data shows that Chinese manufacturing companies' R&D investment reached Rmb1.4trn in 2018, equal to 75% of the level in the US. Second, the investment structure is relatively fragmented. Sectors that are oriented toward technological innovation account for less than 50% of the R&D investment



	Product innovation				Process innovation			
	China	US	Japan	Germany	China	US	Japan	Germany
Manufacturing	28%	33%	28%	20%	34%	41%	29%	35%
Resource intensive								
Chemicals	31%	42%	18%	56%	33%	41%	36%	53%
Metal products	25%	20%	18%	25%	27%	35%	37%	39%
Paper and printing	20%	27%	17%	24%	24%	38%	36%	34%
Technologically innovative								
Computers	51%	48%		66%	48%	39%		55%
Electronics	45%	41%	21%	42%	42%	38%	36%	47%
Medicine	39%	42%		57%	45%	46%		62%
Capital intensive								
Machinery	39%	34%	23%	51%	38%	38%	34%	49%
Transportation equipment	39%	36%	13%	46%	39%	39%	36%	46%
Nonmetallic products	14%	21%		29%	18%	30%		45%
Labor intensive								
Food and beverages	26%	32%	26%	24%	27%	40%	36%	32%
Textile and clothes	21%	27%	16%	32%	22%	31%	35%	38%
Furniture and others	21%	22%	17%	38%	22%	32%	29%	38%

Fig. 6.6 Number of manufacturing companies conducting product innovation and process innovation. *Note* We use 2015–2017 data for US and Japan; 2017 and 2019 data for Germany; and 2016–2018 data for China. *Source* NSF, ZEW, Japan Science and Technology Agency, *China Statistical Yearbook on Science and Technology*, NBS, CICC Global Institute, CICC Research

in the manufacturing industry in China[12] (vs. 80% in the US). In addition, basic R&D projects only account for 0.3% of the R&D investment in China's manufacturing industry, while investment in industrial application and test-related projects is relatively high. Third, investment in R&D staff needs to be improved. Equipment accounts for a high percentage of Chinese manufacturing companies' R&D expenses, while investment in R&D staff remains insufficient in China.

Mismatch between R&D and production, and between production and application also weigh on innovation capability. Regarding the mismatch between R&D and production, the crucial problem is a lack of commercialization of advanced technologies. For example, China has more patents on electrical equipment and engines than the US, Japan, and Germany. However, the commercial use of advanced technologies remains limited in the domestic electrical equipment and engine industries. As for the mismatch between production and application, developing and improving core devices requires sustained feedback from customers, in our view. Companies need to keep fine-tuning parameters and technologies in accordance with the use of their products.

We also see deeper reasons for the weaker innovation capability of China's manufacturing sector.

China's manufacturing industry is export-oriented. The integration of its manufacturing industry into the global industrial value chain gives China access to innovation resources, but reduces its motivation to independently improve R&D capability. High-tech products as a percentage of China's exports have stayed at 40% since the country's accession to the World Trade Organization (WTO) in 2001, while the percentage of high-tech products in its imports has increased to 60%.

Companies' emphasis on capacity expansion and lack of investment in basic R&D projects weigh on the innovation capability of the manufacturing industry. Chinese manufacturing companies have higher capex than their counterparts in the US, Japan, and Germany, but their R&D investment remains relatively low.

We note that nearly half of the listed manufacturing companies in China are recognized as high-tech companies. As a result, the effective tax rate of the manufacturing industry in China is lower than that in the US, Japan, and Germany (except for the pharmaceutical and metal product sectors, Fig. 6.7). The low effective tax rate for a wide range of manufacturing companies may play a limited role in stimulating innovation, in our view.

Regarding direct R&D subsidies, according to the OECD, these subsidies account for less than 50% of government subsidies for companies in China. The subsidy intensity is high at 0.21% in the US, with direct R&D subsidies representing around 66.7% of US government subsidies for companies (Fig. 6.8).

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[12] The manufacturing industry is divided into four sectors, i.e., labor intensive, capital intensive, technological-innovation-oriented, and resource empowered sectors, by Zhang, H., Cheng, X. (2020). (The Analysis of national innovation model and evaluation system of indicators, Statistical Research, (7)) and Liu, L., Zhang, T., Moulan, Z. (2020). (An Empirical study of the evaluation of innovation policies on the advanced equipment manufacturing industry, Science Research Management, (1)).

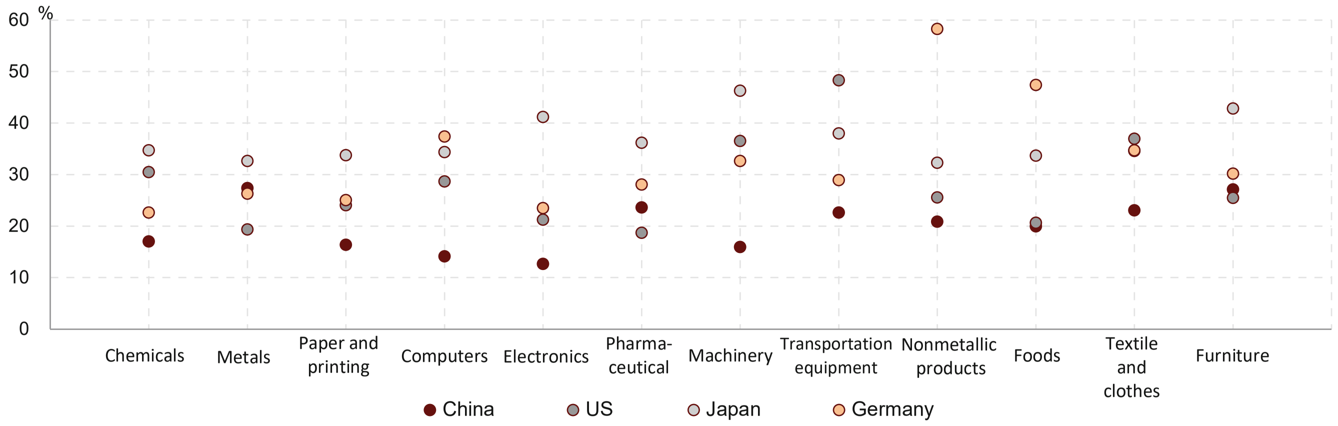

Fig. 6.7 Effective tax rates in China, US, Japan, and Germany. *Note* We base effective tax rates on listed companies' FY20 data. *Source* Bloomberg, CICC Global Institute, CICC Research

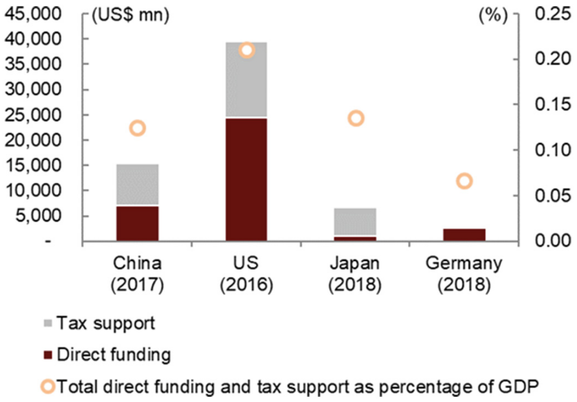

Fig. 6.8 R&D subsidies in China, US, Japan, and Germany. *Source* OECD, CICC Global Institute, CICC Research

6.3.2 Cost Efficiency and Value Chain Security of China's Logistics Industry

According to data from the Ministry of Transport, in 2019, China's logistics costs totaled Rmb14.6trn, accounting for 14.8% of GDP; logistics costs for the US were Rmb11.1trn, representing 7.6% of GDP. Logistics costs' absolute value and share of GDP are higher in China than in the US.

Meanwhile, China's per tonne-km logistics costs were 35% lower than the US's. In 2019, China's freight volume (47.1bn tonnes) was 2.7 × that of the US (17.7bn tonnes), and the turnover volume of freight transport (nearly 20trn tonne-km) in China was 2 × that of the US (nearly 10trn tonne-km). Therefore, China's per tonne-km logistics costs (Rmb0.73) were 35% lower than that of the US (Rmb1.12). Specifically, China's per tonne-km transport costs (Rmb0.39) were 47% lower than that of the US (Rmb0.73), and China's per tonne-km warehousing costs were 40% lower than that of the US. As a result, we think China's logistics costs are not high.

However, we do not believe that low logistics costs directly lead to high efficiency. First, China achieves low logistics costs at the expense of profit margin. In the last decade, the average profit margin of the domestic logistics industry was around 3.7%, 4.4 ppt lower than that of the US (vs. 8.1% in the US) (Fig. 6.9). Second, China's labor efficiency is only one-fifth of that of the US. According to the National Development and Reform Commission, over 50mn people work in China's logistics industry, nearly 10 × the number in the US (5.2 mn), which means the labor efficiency of the logistics industry in China is only one-fifth of that of the US (and the average salary in the domestic logistics industry is also one-fifth of that of the US).

What caused the efficiency gap in logistics? We think China has achieved world-leading consumer business efficiency but lags behind the US with regard to corporate business. For example, the per capita package handling volume of express delivery is 190 pieces in China compared to 60 in the US. Using JD and Amazon's warehouse

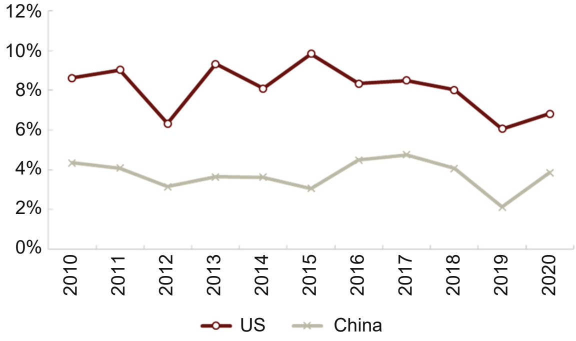

Fig. 6.9 Comparison of Chinese and US logistics companies' operating profit margin. *Source* Wind, CICC Research

operations as further examples, the daily package delivery volume, sorting efficiency, and accuracy of JD's "Asia No. 1" warehouse are close to that of Amazon's warehouses. Although the efficiency of consumer logistics businesses is already high in China, the proportion of consumer business in the sector is low. For example, the scale of China's express delivery market is around Rmb900bn, representing only 6.2% of China's logistics costs (Rmb14.6trn). Therefore, we think it is the corporate business that mainly drags the efficiency of China's logistics.

We attribute the low efficiency of China's corporate logistics businesses to three factors. First, low automation rate. According to MIR Databank, the automation rate of logistics was 20% on average in China versus 80% in developed countries. According to Cushman & Wakefield, the proportion of modern warehousing and logistics facilities was 7% by gross floor area (GFA) in China versus 22% in the US. The second is low transport efficiency. According to the Ministry of Transport, the empty-loaded rate of freight transport was 40% in China versus 10–20% in developed countries in 2019. The third is the relative lack of integrated transport. According to the Ministry of Transport, combined sea-rail transport volume made up only 2.6% of Chinese ports' transport volume in 2020 versus 20–40% for developed countries.

In addition, China is not a strong player in international logistics, which limits its ability to build reliable supply chains.

China has a trade deficit in transport services. Its goods trade is growing rapidly. However, unlike the international goods trade, which has seen a trade surplus for some time, transport service remains the second largest area for which China has a trade deficit (second only to tourism). According to NBS, the transport services trade deficit reached US$58.84bn in 2019.

China is not a strong player in shipping. Most import trade adopts cost (C) terms. As foreign export service providers have their preferred forwarding and shipping companies, most of China's import trade adopts cost and freight (C&F) or cost, insurance, and freight (CIF) pricing, which means that exporters are responsible for transportation. However, most of China's export trade adopts F terms, or free on board (FOB) pricing. Most foreign shipping companies are familiar with local ports and transportation, and as smaller domestic companies have weak bargaining power in exports, foreign importers are responsible for transportation.

Domestic airlines only account for around 35% of international airfreight volume in China in 2019. According to the International Air Transport Association, airfreight only accounts for 0.2% of international freight by volume but 36% by value in 2019. According to the Civil Aviation Administration of China, in 2019 foreign airlines account for around 65% of the international airfreight volume in China, with DHL, UPS, and FedEx comprising nearly 75% of the international express delivery.

China's all-cargo aircraft transport capacity is only 11% that of the US in 2021. According to Planespotters.net, providers of contract fulfillment for door-to-door services only make up 37% of China's all-cargo aircraft transport capability. In contrast, FedEx, UPS, and Amazon together account for 73% of all-cargo aircraft transport capability in the US. As of January 2021, China had around 185 all-cargo aircraft with a total capacity of around 8,903 tonnes, which is only 11% of the US's total of 79,906 tonnes (from 1,125 aircraft).

We attribute China's weak presence in international logistics to developed countries' first-mover advantage in the market.

6.4 New Opportunities for Manufacturing and Logistics

In our view, despite the challenges mentioned earlier, there are new opportunities for China's manufacturing and logistics sectors. As the smile curve is likely to flatten in the digital economy, manufacturers are embracing more innovation-driven development opportunities. The logistics sector is set to benefit from the large domestic market with stronger economies of scale, and technology can play a greater role here.

6.4.1 Digital Economy Empowers Manufacturing: The Smile Curve is Likely to Flatten

The manufacturing sector has shifted to automation from large-scale standardized production, and it is likely to see diversification and customization due to continuous technological advances. Looking ahead, we think that the digital economy will alter the nature and form of manufacturing, presenting innovation-driven development opportunities to manufacturers.

The "smile curve" depicts how the value added varies across the different stages of bringing a product to the market. Value added at the R&D and marketing stages is typically higher than that at the manufacturing stage, as the barriers to entry are lower for manufacturing firms, competition is fierce, and these firms are likely to be replaced.

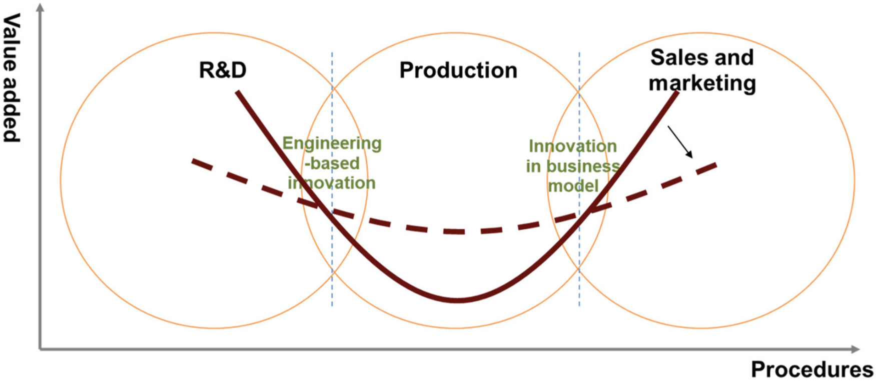

Fig. 6.10 We expect the smile curve to flatten due to the digital economy. *Source* CICC Global Institute, CICC Research

The smile curve is likely to flatten in the digital economy for three reasons (Fig. 6.10). First, the relationship between manufacturing and innovation is likely to become closer. Digital technologies enable manufacturing companies to simulate and verify innovative products at the R&D stage, thereby shortening the duration of the R&D-to-production period. Second, digital technologies can help cut costs and improve operating efficiency in manufacturing, warehousing, and logistics. Third, manufacturing-related services facilitate innovation activities. Manufacturing companies, thanks to the digital economy, can have access to demand estimates and IT-enabled interactive management systems. We think that the digital economy will help processing and assembly companies roll out manufacturing-related services, propel the shift from traditional manufacturing to service-oriented manufacturing, and stimulate innovation.

Innovation presents new opportunities for manufacturing in China. For engineering-based innovation, integration of production and R&D improves competitive advantages of manufacturing companies.

China excels at manufacturing, while developed countries have gained an advantage in R&D. They have maintained this competitive advantage due to the separation between manufacturing and R&D. We think that the relationship between manufacturing and R&D will become closer as the smile curve is likely to flatten amid the growth of the digital economy. Thus, Chinese manufacturing companies will likely achieve engineering-based innovation by leveraging their advantage in the manufacturing industry chain.

The use of digital technologies shortens the technology upgrade cycle. Improving manufacturing techniques and advanced technologies requires multiple steps, i.e., R&D, tests, and enhancing the level of technological maturity. Such steps are not only capital and human resource intensive, but also take time. Digital technologies and models can simulate components, products, and manufacturing processes to shorten the technology upgrade cycle and help companies improve their competitive advantages.

The digital economy increases the interaction between manufacturing and R&D projects, which can help drive innovation. For example, additive manufacturing can help companies shorten the material and equipment R&D cycles, simplify the R&D and design process, and propel technological innovation, in our view. We think that the engineering-based innovation, empowered by China's industry chain advantage, and the design innovation amid the growth of the digital economy, will present new development opportunities for the manufacturing industry in China.

For innovation in business models, integrating production and application enables manufacturing companies to expand into more industries.

We think that manufacturing companies will roll out manufacturing-related services as the relationship between manufacturing and services is likely to become closer as the smile curve flattens.

First, we expect manufacturing activities to require more producer services—design, R&D, and management consulting services, among others—as well as energy and raw materials. The need for innovative design, customized services, supply chain management, network-based collaborative manufacturing services, service outsourcing, smart services, financial services, systematic solutions, and other producer services will likely increase. Second, we think that manufacturing companies will pay closer attention to the value of their services in the whole life cycle of their products. Manufacturing-related services will improve the customization, collaboration, and sharing economy in the manufacturing industry, in our view.

Manufacturing companies have benefitted from China's large market, and we think going forward, they will continue to drive manufacturing innovation thanks to the integration of manufacturing and services. They are likely to achieve diversity and innovation-driven growth as customer demand varies, competition is tough, and profits are typically higher in a large market.

6.4.2 Developing Domestic and International Logistics

6.4.2.1 How Much Potential is There for China's Sizable Logistics Market?

Domestic logistics market should enjoy strong economies of scale given its large size.

First, China has a large population and fragmented resources, creating high demand for flows via transportation networks. China's large population (indicating large logistics demand) and land area (fragmented resources) create ample demand for transport. We note that the degree of utilization of network-based transport sectors (e.g., highways, high-speed railways, and airports) is high in countries with larger populations, which helps them realize the optimization of technology and operation models, thus boosting logistics efficiency.

Second, a large logistics market implies multiple layers of demand, and business model innovations may create economies of scale. As large countries have greater demand for logistics and different layers of consumption (some traditional, some innovative, and with consumers at different consumption levels), companies need to constantly develop new business models to keep up with demand. For example, the rise of e-commerce platforms in the early twenty-first century changed consumers' shopping habits (shifting from offline to online), which boosted the development of express delivery.

Third, the logistics sector benefits from the more favorable environment for technology application and economies of scale found in large countries. New technologies are usually expensive due to higher R&D expenses. However, we think it is easier to have new technologies widely applied in a large logistics market given its economies of scale as the price of new technology will gradually fall with greater penetration. Technology upgrades can also help raise logistics efficiency.

A comparison of leading logistics companies in subsectors illustrates the domestic logistics industry's significant growth potential. Based on data accessibility and company comparability, we compare leading Chinese and US logistics companies from three subsectors: Freight forwarding (KNIN and Sinotrans), express transportation (ODFL and ANE), and express delivery (UPS, FedEx and SF-Express). In general, leading Chinese companies' revenue and profit are only one-quarter to one-half that of their US counterparts. Profit margins for Chinese logistics companies are also lower than that of US names (1.2 ppt lower for freight forwarding, 7.8 ppt lower for express transportation, and 4.0 ppt lower for express delivery).

As the US has more concentrated upstream and downstream logistics industries, which have clearer competitive landscapes following industry consolidation, its leading companies are larger and enjoy higher profit margins. We expect the domestic logistics industry to become more concentrated and its profit margin to rise. In our view, a more concentrated logistics industry should also help lower costs due to economies of scale.

6.4.2.2 How to Improve Logistics Efficiency and Unleash the Logistics Industry's Growth Potential?

China has diverse application scenarios for 5G and AI, and we expect it to catch up with other countries in logistics in the digital economy.

How can China improve its logistics efficiency? From a macro perspective, we expect the digital economy to make logistics services more tradable and digital technology more accessible.

Digital economy makes logistics services more tradable, which may boost efficiency. Historically, services have been considered non-tradable, but the digital economy enables the completion of tasks or trade with no interactions between humans, which was previously impossible. The COVID-19 pandemic also highlighted the role of the digital economy. We think trade creates competition, and competition may bring new ideas, concepts, and technologies, resulting in higher sector efficiency. We thus expect more tradable logistics services to help increase sector efficiency.

In the digital economy, digital technologies (e.g., 5G, AI, and cloud computing) are more accessible and can be more easily applied, which may help solve the logistics industry's pain points, including labor intensity, high cost, and poor management. The traditional logistics industry is labor-intensive, but China's demographic dividend is fading. Meanwhile, the logistics market is quite fragmented, with low levels of digitalization and informatization. In the era of the digital economy, we think technologies (e.g., 5G, AI, and cloud computing) have become more accessible and more easily applicable, which will notably optimize logistics companies' business procedures and operations.

From a micro perspective, China's logistics industry is increasing R&D spending, and technology helps reduce logistics costs as well as improve efficiency. R&D spending in China's logistics industry is increasing. The country's logistics R&D expenses/revenue ratio rose to around 0.4% in 2020 from 0.1% in 2016 (with 2016–2020 five-year average at 0.28%), but its R&D expenses/revenue ratio is only one-third that of the US, whose 2016–2020 five-year average is 0.89%. However, the Chinese express delivery sector's R&D expenses/revenue ratio has risen to 1.3% in 2019 and 2020, which is already higher than that of the US express delivery business and equivalent to that of the US logistics industry in 2000 (Fig. 6.11).

Given China's 5G and AI technologies and data from its large logistics market, we expect technology to make logistics smarter and more efficient in the digital economy. AI and 5G are being used to replace humans in simple and repetitive tasks, assist and empower humans (e.g., unmanned trucks, unmanned aerial vehicles, unmanned warehouses, express automatic sorting, smart parcel lockers, smart customer service), and optimize business processes and management (e.g., warehouse management, transport management, smart maps, route planning). The benefits of technology can be seen in the case of the Manbang platform, a vehicle-goods matching platform in China. As a result of efficiencies created through the use of technology, drivers on Manbang can currently drive 12,000 km per month (up from 9,000 km) and take

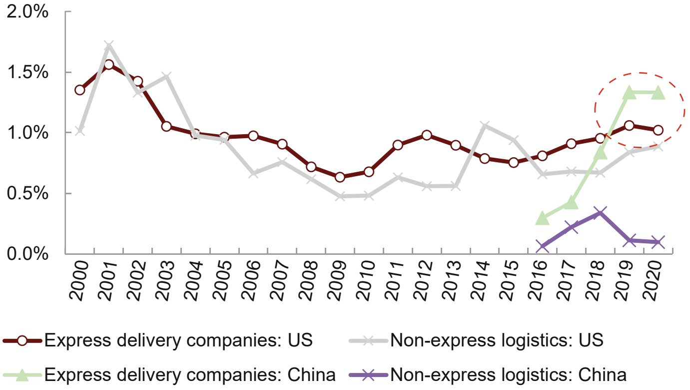

Fig. 6.11 R&D expenses/revenue ratio of express delivery companies and other logistics companies. *Source* Ministry of Transport, U.S. Bureau of Transportation, CICC Research

an average of 20 orders per month (up from 14). Their empty-loaded rate has fallen to 34% from 38%. We estimate a 1% decline in the empty-loaded rate of domestic trucks would lower logistics costs by around Rmb17bn and cut carbon emissions by around 7.20 mn tonnes.

6.4.2.3 Diverse Modes of Transportation and Cross-Border E-commerce May Change the Competitive Landscape of International Logistics

As previously mentioned, China is not a strong player in international logistics, which limits its ability to build reliable supply chains. We now examine the three trends that are shaping the international logistics system, namely the regionalization of supply chains, the more diverse cross-border transport as well as rail transport's increasing share, and synergies between domestic brands and logistics companies' overseas expansion. These trends may change the competitive landscape of international logistics, offering China new opportunities to develop its international logistics system, in our view.

Intra-regional logistics is growing as the trend of "deglobalization" becomes more visible. According to the WTO, global trade has weakened since 2008 (we evaluate global trade by calculating the ratio of total exports to output), showing a visible deglobalization trend. Deglobalization has two major impacts on the international trade landscape. First, industry chains are becoming more regionalized. To diversify procurement, the US and European countries are expanding the scale of production and supply in surrounding countries to develop a greater number of shorter supply chains, as demonstrated by a World Bank Group report.[13] Intra-regional cooperation has grown in depth and breadth. Second, supply chain localization may accelerate. Developed countries have focused more on manufacturing since the 2008 financial crisis. For example, the US has introduced a series of policies to encourage advanced manufacturing companies to return to the country.

Cross-border transportation is becoming more diverse, with land and airfreight playing greater roles. According to the WTO, shipping's share of total cargo transport service fell by 10 ppt over the last decade. Land transportation's share of cross-border transportation has risen by 9 ppt in the last decade and has grown further despite the COVID-19 pandemic. Global airfreight volume rose steadily from 2009 to 2018, with its share of global export freight rising by 2 ppt in the last decade. We note that developing countries have a greater voice in land and air transport than in shipping, highlighting the strategic importance of developing new global transportation channels.

Cross-border e-commerce is supporting Chinese brands and logistics companies' overseas expansion. In recent years, the cross-border e-commerce industry

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[13] World Bank Group, OECD. (2019). Technological innovation, supply chain trade, and workers in a globalized world.

has become more mature. We think the short distribution chain and high effectiveness of the logistics system have helped cross-border e-commerce companies achieve data sharing and have brought brands directly to consumers. According to 100ec.cn,[14] China's cross-border e-commerce trade volume grew at a CAGR of around 58% over 2015–2020. We expect cross-border e-commerce businesses to maintain a CAGR of around 20% over 2021–2025, with total exports to reach nearly Rmb5trn by 2025. Cross-border e-commerce platforms may also contribute to the globalization of Chinese logistics by allowing Chinese exporters to select logistics companies.

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[14] 100ec.cn, (2020). Chinese cross-border e-commerce market data report, https://www.100ec.cn/detail--6592730.html.

Chapter 7
Supporting Innovation: Unquenchable Flames

Abstract Innovation is the source of economic growth on a per capita basis and an essential way to improve standards of living. Thus, developing innovation capabilities is fundamental for modern economies. The innovation system of a country includes market-based cooperation and interaction between enterprises, universities and government, as well as innovation-related framework conditions such as infrastructure, policy framework, and macroeconomic environment. In this way, a complete ecosystem nurtures innovation.

China has been establishing an innovation system that conforms to its national conditions. The country's innovation system shows notable competitive advantages given its enormous domestic market system and world-leading physical infrastructure. China has also established innovation-related systems and policies, including those for anti-trust and IP protection. It is able to provide a macroeconomic environment that encourages overall innovation. For example, it has established a modern enterprise system, and continues to strengthen the provision of financial support for technological innovation. Facing changing situations at home and abroad, China continually upgrades its approach to integrating into the global innovation framework, and the country is shifting from a latecomer in traditional segments to a frontrunner in new fields.

Regional innovation centers are also an important part of China's national innovation system. They are essential for implementing national innovation policies. Regional innovation centers in different areas have their respective advantages, and we expect them to improve further, with Silicon Valley and Germany providing valuable models.

We should not neglect the government's role in coordinating and supporting technological innovation. In China, the government emphasizes its role in promoting innovation, especially during key periods and for core industries. It can make targeted use of market resources and policy measures when supporting corporate R&D, and improve the efficiency of its financial support to innovations in the private sector. We also believe that it is important for the government to make reasoned decisions, to increase the flexibility of R&D management system, and ultimately, to make full use of the new system for mobilizing resources.

CICC Research, CICC Global Institute, *The Rise of China's Innovation Economy*,
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The government also plays a vital role in financing innovation. While innovation needs external financial support, the financial industry does not always spontaneously invest in it. We attribute this to the constraint from financial cycles, a high risk of failure, and an innovation paradox. The government could correct such failures to enable the financial system to better support innovations, including allocating appropriate financial resources to different types of innovations. For example, the private equity market has limited financial resources, but it is better positioned to support smaller firms, which have a stronger desire to promote "radical innovation". The stock market could create a divesting channel for venture capital to make the private equity market more active. Large firms tend to rely on "incremental innovation", which could be supported by banks that naturally prefer stable cash flows and ample collateral.

Currently, China is catching up with advanced economies, and we expect the country to become a global frontrunner in technology in the long term. A number of domestic industries (e.g., semiconductors) are facing vertical risks. In such sectors, the "catching up" innovation financing model in which large banks offer ample credit resources to big companies may need to play an important role. As such, China should improve the "leading" innovation financing model where medium-and-small firms rely on capital markets to raise money to fund innovation. Thus, the financing models for both radical and incremental innovations are key to China.

7.1 Promoting Innovation is a Fundamental National Task

Innovation is a major source of a country's economic growth and is essential for sustainable development. With the rapid development of computer and information technology in the 1980s, the mobility of knowledge has increased, and people's understanding of innovation has shifted from a linear model in its early stage (from basic scientific research to R&D investment, and then to innovation achievements) to a non-linear systemic and ecosystem-based model. Innovation is highly reliant on the interaction among enterprises, universities, the government, and other entities in terms of knowledge, human capital, and funds. [1] Such interaction, in turn, depends on a country's market system, [2] social infrastructure (including education, scientific research, and social security system), and macroeconomic policy environment[3]

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[1] The private equity market in this report refers to the market for trading of shares issued by unlisted companies, including VC, PE and angel.

[2] In this report, the "catching up" innovation financing model refers to the innovation financing model where large banks offer ample credit resources to big companies to promote incremental innovation. It helps China catch up with the world's technology powers. The "leading" financing model is the innovation financing model where mid- and small-sized companies use the money from capital market to fund innovation. It can help China become a global frontrunner in technological advances.

[3] Lundvall (1992); Freeman (1995); OECD (1997).

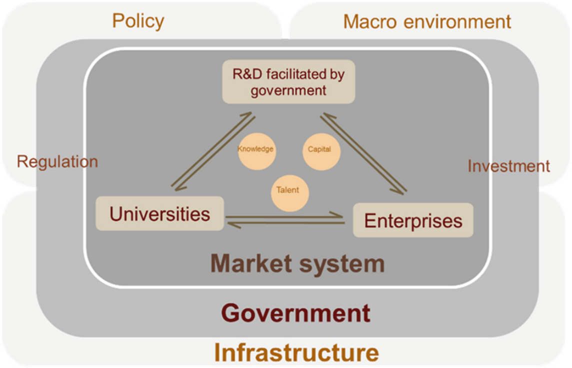

Fig. 7.1 Schematic diagram of national system of innovation. *Source* CICC Global Institute

(including finance, fiscal, and trade policies). These together constitute a "national system of innovation"[4] in a broad sense (Fig. 7.1).

At the core of the national system of innovation stand the market system and the enterprises, universities, and government within the system. Since the 1990s, the Organization for Economic Cooperation and Development (OECD) has been analyzing and evaluating the effectiveness of the national system of innovation in various countries, focusing on the flow and diffusion of knowledge, and emphasizing four kinds of interactions between the three types of innovation entities (namely enterprises, universities, and research institutions established by the government): Cooperation in innovation between enterprises; cooperation in innovation between enterprises, universities, and governments; the diffusion of knowledge; and the flow of innovative human capital among the three entities.

Policies and institutions that promote the flow of innovation resources outside the market constitute the ecosystem for innovation. International organizations such as the OECD and the EU call it the "framework conditions of innovation"[5]. We divide the framework conditions into three major categories—infrastructure, institutional system, and macroeconomic environment—as shown in Fig. 7.2.

Infrastructure is the enabling environment that guarantees and promotes the orderly flow of factors of production and the regular operation of the market. It includes physical infrastructure, social infrastructure, and financial infrastructure. The institutional system is the direct means for the government to manage the market,

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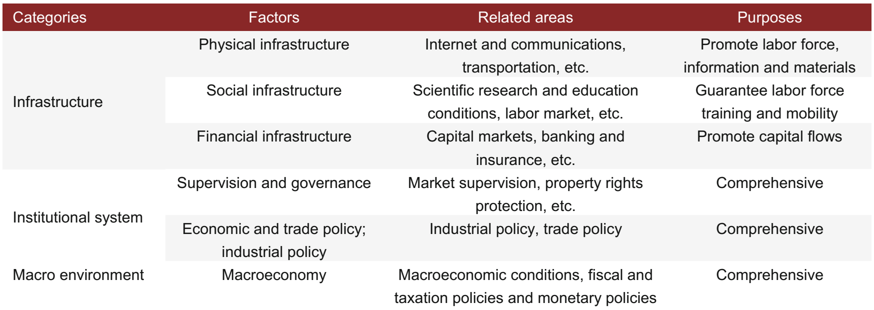
[4] The concept of "national system of innovation" can be traced back to historic economic wisdom. In the late nineteenth century, Germany's economy started to take off, driven by the achievements of the Industrial Revolution in the UK. Economist Friedrich List then introduced the concept of the "national system of political economy". List emphasized the role of technology transfer and innovation in a country's ability to catch up economically and believed that the government should play a leading role. Given its focus on technology transfer and innovation, this concept is basically equivalent to the concept of "national system of innovation" that was introduced later.

[5] Costa, P., Ribeiro, A., van der Zee, F., Deschryvere, M. (2016). Framework conditions for high-growth innovative enterprises. OECD (2008). The OECD reviews of innovation policy: China.



Categories	Factors	Related areas	Purposes
Infrastructure	Physical infrastructure	Internet and communications, transportation, etc.	Promote labor force, information and materials
	Social infrastructure	Scientific research and education conditions, labor market, etc.	Guarantee labor force training and mobility
	Financial infrastructure	Capital markets, banking and insurance, etc.	Promote capital flows
Institutional system	Supervision and governance	Market supervision, property rights protection, etc.	Comprehensive
	Economic and trade policy; industrial policy	Industrial policy, trade policy	Comprehensive
Macro environment	Macroeconomy	Macroeconomic conditions, fiscal and taxation policies and monetary policies	Comprehensive

Fig. 7.2 Framework conditions for innovation. *Source* CICC Global Institute

maintain order, and guide technological and industrial development. It comprises legal and regulatory systems and conventional economic policies, and can minimize the transaction costs among all parties.[6] The macroeconomic environment includes fiscal policy, tax policy, and monetary policy, among others.

Infrastructure facilitates the flow of factors of production, the institutional system ensures that production factors can function normally, and the macroeconomic environment ensures that innovation activities are carried out in a stable and predictable business and economic environment. These framework conditions serve as public goods, and the responsibility of the government is to create public goods that can promote the flow of factors required for innovation, playing the role of the "visible hand".

The establishment of a sound national system of innovation requires coordination and cooperation between the market system and public policies to improve the effectiveness of innovation in three ways, namely R&D investment, the demand channel, and the flow of knowledge.

The first move is to optimize R&D investment in both quantity and quality. In terms of quantity, R&D investment should be at the most effective level, being sufficient and reasonable.

In terms of quality, R&D investment should be well-structured, i.e., the distribution of R&D input in basic research and application development should be optimal.

The second is to expand or create demand for innovative products. Successful innovative firms such as Apple create demand for their new products, and the government can create demand for innovation. For example, the government's goals of reaching peak carbon emissions and achieving carbon neutrality and the related policies have driven demand for environmentally friendly technology products and services. Market size is also crucial to innovation as market capacity determines innovator costs and returns.

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[6] Powell, W. W., DiMaggio, P. J. (1991). The New institutionalism in organizational analysis. University of Chicago Press.

Third, the government could promote interaction and flow of knowledge among different innovation entities, as well as improving the social rate of return of innovation.

Both the market and the government are indispensable in the national innovation system, complementing one another. The government can correct market failures of innovation activities, making its role in innovation far more significant than in conventional economic activities. This is mainly because of the following two points.

Innovation has positive externalities. It is the process of generating knowledge. Once knowledge is generated, the cost of innovation is then fixed, regardless of how many people learn to use the knowledge. Market mechanisms often lead to an insufficient supply of incentives for innovation activities with positive externalities.

The results of innovation are also highly uncertain. Such uncertainty is more difficult to predict than risk events and is impossible to eliminate or reduce through insurance. Due to the high level of uncertainty, the market mechanism featuring perfect competition usually leads to insufficient innovation.

Coordinating the roles of the market and the government is the key to improving the national system of innovation, and it is usually difficult to strike a balance between the two. The first challenge is to measure the benefits of innovation. The knowledge produced by innovation is almost freely transmitted. The more an innovation activity relies on basic R&D, the greater its externality would be, and the transmission of knowledge cannot be traced or measured. More importantly, it is difficult to measure the inputs and results under different policy assumptions as such assumptions can deviate from the reality. This makes it difficult to evaluate different policy combinations empirically. However, we still seek to conduct policy analysis to provide suggestions for China to improve its innovation system.

7.2 The Practicalities of Establishing a National Innovation System

Since the introduction of the reform and opening-up policy more than four decades ago, China has gradually established a market system and modern enterprise system, as well as world-leading hardware infrastructure, laying a solid foundation for a national system of innovation. Especially since China joined the WTO in 2001, the domestic market has witnessed unprecedented expansion, and a number of world-leading companies have emerged, marking China's great progress in developing its innovation system.

In 2005, the Ministry of Science and Technology of China commissioned the OECD to conduct research on innovation policy. Renowned Chinese and foreign scholars in technology innovation policies spent three years in completing the report *OECD Reviews of Innovation Policy: China.*[7] The report states that China should learn from the successful experience of OECD countries, including adjusting the role

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[7] OECD (2008). The OECD reviews of innovation policy: China.

of the government, improving the framework conditions for innovation, enhancing human capital in science and technology, improving the collection of science and technology innovation policies, maintaining strong support for public R&D, and strengthening industry-university-institute cooperation. Looking back at the past decade, we note that the Chinese government adopted some of the suggestions made in the OECD report. China also explored a pathway to developing its innovation system that conforms to its national conditions, something that went beyond the parameters of the report.

7.2.1 Framework Conditions for China's Innovation System

The enormous domestic market is a major advantage of China's innovation system. From the perspective of the national system of innovation, China's market system shows a notable competitive advantage thanks to large market capacity and extensive coverage.[8] In the twenty-first century, the ubiquitous internet technology and the advancement of infrastructure construction nationwide have accelerated the process of market integration. So far, China has become the world's largest market, with total retail sales of consumer goods surpassing that in the US. The enormous market implies substantial demand for innovative products and high potential profits from innovation, which in turn provides a powerful incentive for innovation activities (for details, please refer to Chap. 2 of this report).

A unified labor market promotes the flow of human capital and facilitates the diffusion effect of knowledge and technology. A large-scale unified market has taken shape in China, mainly driven by changes in the number of employees in the industry amid the reform of the household registration (*hukou*) system and reform of SOEs in recent years. In particular, the reform of the *hukou* system played the biggest part in improving the efficiency of labor allocation in China.[9] According to the *China Torch Statistical Yearbook*, from 2010 to 2020, the transaction value of China's technology market increased by 11 times, accounting for 1.6% of total GDP.

China has world-leading physical infrastructure, and is improving its social infrastructure for technological innovation. China leads the world in terms of transportation and information and communication technology (ICT) infrastructure, which helps reduce transaction costs and increases the profitability of enterprise innovation. For example, high-speed rail (HSR) in China accounts for more than 60% of the world's

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[8] Regarding the relationship between market size and innovation, Adam Smith believed that the division of labor is limited by the extent of the market. He attributed Britain's rapid increase in labor productivity in the seventeenth and eighteenth centuries to its successful international trade strategy. Britain's expansion of global trade promoted improvements in division of labor in manufacturing, and division of labor meant specialization and perfect competition among various new technologies, which eventually gave birth to the Industrial Revolution (Smith, 1776).

[9] National Institute of Development and Strategy, Renmin University of China (2019). Compilation of China Labor Marketization Index.

total operating mileage, and is the world's fastest.[10] In 2020, the penetration rate of mobile phones in China reached 113 units per 100 people, and mobile internet coverage was almost universal.[11] Backed by leading ICT infrastructure, the Chinese government is at the forefront of digital governance, and plays an important role in supporting innovation in the digital economy era.

In addition, China has completed the development of social infrastructure, including education, scientific research, and social security, providing necessary public goods for the development of science and technology. For example, the Chinese government accounts for a large share of R&D expenditure in China. In 2020, China's total R&D expenditure reached Rmb2.2trn, ranked No.2 after the US; and the government contributed 20% of China's total R&D spending, mainly to fund government-affiliated scientific research institutes and universities.

Antitrust and intellectual property (IP) protection systems are taking shape in China. The government's governance and regulatory policies for technological innovation mainly focus on these two aspects. As for antitrust policies, we believe that three factors deserve attention. First, technological innovators will maintain some monopoly power for a period, and the corresponding monopoly profit is a necessary reward for them. Second, it is difficult for monopolistic enterprises to develop advantages that are large enough to avoid competition or to limit the entry of competitors. Finally, large companies and small players can also be partners rather than just competitors. It is technological innovation that typically empowers small businesses to challenge the leadership of large companies, thus facilitating cooperation between the two.

China's IP system originated from the "863 Program".[12] After nearly 30 years of development, IP rights covered by the scientific research under the program have expanded to ownership, right to use, right to transfer and right to benefit. The ownership of IP rights has also gradually shifted from government departments to institutions and researchers, thereby providing stronger economic incentives for scientific research institutions and individuals.[13] Looking ahead, China should ensure IP is protected to strike a balance between the incentive of knowledge production and the diffusion of knowledge. The patent system is a tool suitable for realizing this goal, under which innovators disclose technical secrets in exchange for a number of years of protection.

China has developed a favorable macroeconomic environment for technological innovation. First of all, the Chinese government attaches great importance to the stability and consistency of macroeconomic policies. In the past 20 years, China has maintained a stable domestic economy, providing a favorable environment for innovation, even during financial crises in the US, Europe, and emerging markets.

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[10] Sources: Statista, Omio.

[11] Sources: Global Competitiveness Report, MIIT, NBSC.

[12] "863 Program" is the nickname of China's National High-Tech R&D Program initiated in March 1986.

[13] Su, J. (2014). Public policy for science and technology: An introduction. Beijing: Science Press.

At the same time, China's nominal interest rate has dropped from double-digit levels to a level close to that in developed countries and has remained low since 1995, increasing investment returns for innovation activities. Moreover, China's average CPI inflation has been relatively moderate, at about 3% in the past 20 years. This not only provides rewarding market prices to innovative products, but also avoids rapid depreciation of current assets or high nominal interest rates that are detrimental to technological innovation.

In addition, a relatively high tolerance for asset bubbles usually benefits technological innovation. Human development has been driven by rounds of technological changes, each accompanied by bubbles created by financial capital and production capital.[14] The social rate of return is higher than the internal rate of return to innovators because new technologies have positive externalities. Even after the bubble bursts, the socio-economic benchmark level under the new equilibrium will still be higher than that of the previous round.[15] Many studies in developed countries have shown that emerging, R&D-intensive companies are more reliant on equity financing. They tend to issue new shares to raise funds during the bubble to accumulate resources for innovation.[16] However, regulators should be aware that the bubble has to be triggered by technological innovation rather than speculative activities, and the scale of the bubble or the damage after it bursts should be manageable.

China has also established a modern enterprise system,[17] including cultivating a number of competitive enterprises and building an environment conducive to the growth of innovative enterprises. Enterprises are the biggest driving force of innovation.[18] Most R&D investment comes from enterprises, and their decisions could determine the outcomes of innovation. Due to the relatively friendly conditions for establishing companies in China, the number of newly registered companies has grown rapidly in recent years. At the same time, local governments, industrial parks, venture capital funds, and small- and medium-sized banks cooperate in leveraging-related market mechanisms. This has helped form a set of mechanisms for discovering, cultivating, and supporting technological innovation enterprises with great potential.

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[14] Brown, J. R., Fazzari, S. M., Petersen, B. C. (2009). Financing innovation and growth: Cash flow, external equity, and the 1990s R&D boom. Journal of Finance, 64(1), 151–185.

[15] Morck, R. (2021). Kindleberger cycles & economic growth: Method in the madness of crowds 28411.NBER Working Paper.

[16] Brown, J. R., Fazzari, S. M., Petersen, B. C. (2009). Financing innovation and growth: Cash flow, external equity, and the 1990s R&D boom. Journal of Finance, 64(1), 151–185.

[17] The modern enterprise system is generally based on a sound company legal person system, with a limited liability system as the guarantee, and a corporate enterprise as the main form. It requires clear property rights, clear powers and responsibilities, separation of government and enterprises and scientific management. Quoted from Wang, X. Wang, X. (2007). Modern company system. China Commercial Publishing House.

[18] Schumpeter, J.A. (1942). Capitalism, socialism and democracy. Harper & Row, New York, (36), 132–145.

China has been strengthening the provision of financial support for technological innovation. With the release of the *National Medium- and Long-Term Program for Science and Technology Development (2006–2020)* in 2006, the central government introduced a series of policy measures and called for the development of a system under which the financial sector supports innovation. Since 2006, the ChiNext board and STAR market have been launched. The ChiNext board was introduced in 2009, and the total market cap of listed companies hit nearly Rmb1.1trn by the end of 2022. The top seven industries by market cap are closely related to technology, and they accounted for over 80% of the total market cap, highlighting the technological attributes of the ChiNext board.[19] The STAR market was launched in June 2019, featuring the adoption of the registration-based IPO system, which streamlines the listing process and lowers the threshold for the listing of technological companies.

Another major achievement is the development of the venture capital (VC) industry. From 2008 to 2018, annual investment by China's venture capital funds rose from less than US$5bn to nearly US$35bn, accounting for 13% of the global total. The amount of money raised by China's VC funds accounted for 21% of the global total, second only to the US.[20] Investment and financing activities in the IT industry have witnessed the fastest growth, with the financing amount once exceeding more than 50% of China's total, before stabilizing at about 40%.[21]

Facing trade-offs between opening up and facilitating indigenous innovation, China upgrades continues to upgrade its approach to integrate into the global innovation framework. In the past 40 years, the innovation activities of Chinese enterprises have mainly focused on learning advanced foreign technologies, and multinational companies have played an important role in diffusing knowledge and technologies. At the same time, a growing number of foreign investors are investing in domestic startups and listed companies.

In practice, China has adhered to the opening-up policy over the years and fulfilled its commitments to the WTO, integrating itself into the global trade value chain and innovation system. First, China has relaxed restrictions on foreign investment substantially since 2010. Even in 2020, when global foreign direct investment (FDI) fell by 35% amid the COVID-19 pandemic, China's use of foreign capital bucked the overall trend to increase by 6.2%.[22] Second, China is playing an increasingly important role in the global value chain. From 2008 to 2020, China's share of global exports rose from around 8.8% to 14.7%, and its share of global imports trended up from 6.9% to 11.5%. In terms of R&D, multinational companies have established more than 2,400 R&D centers[23] in China, covering a wide range of industries.

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[19] Source: Wind, Shenzhen Stock Exchange.

[20] Pedata.cn (2019). National Venture Capital Association (NVCA) Yearbook.

[21] Source: Wind.

[22] According to reports by China Daily and Fox News, in 2020, China surpassed the US in attracting FDI. However, according to UNCTAD's World Investment Report 2020, the Chinese mainland fell behind the US by US$7bn in terms of FAI but including Hong Kong SAR, China has surpassed the US.

[23] Ministry of Commerce, China Foreign Investment Report 2017 and 2019.

Faced with sentiment of deglobalization, China introduced a new economic development pattern that is focused on the domestic economy and features positive interplay between domestic and international economic flows. Given the sudden changes in the international situation in the past five years, China may seek to strike a balance between opening up and accelerating indigenous innovation and domestic substitution, posing new challenges to the development of the innovation system in the country.[24]

Meanwhile, China is shifting from latecomer in traditional segments to "frontrunner" in new fields. The Chinese government is deeply aware that the new round of changes in basic technologies, such as information, energy, and life science may reshape the global industrial structure.[25] Policies have been issued to promote technological innovation in seven strategic emerging industries, namely energy conservation and environmental protection, new generation information technology, biology, high-end equipment manufacturing, new energy, new materials, and new energy vehicles.[26] According to the National Development and Reform Commission (NDRC), over 2015–2019, the average annual growth rate of industrial output of enterprises above a designated size in these strategic emerging industries was 10.4%, while that of the overall industrial sector was merely 6.1%.[27] Backed by such established exposure to new fields, China has been striving to catch up with developed countries and to even become a frontrunner in the new fields and move to high-value-added sectors in the global value chain.

7.2.2 Regional Centers Are Main Components of a National Innovation System

Regional innovation centers are an important part of the national innovation system and are essential for implementing national innovation policies as they are central to development of innovation capabilities. This is because innovation activities are

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[24] Chen, J., Yin, X., Fu, X., McKern, B. (2021). Beyond catch-up: could China become the global innovation powerhouse? China's innovation progress and challenges from a holistic innovation perspective. Industrial and Corporate Change 30(4), 1037–1064.

[25] President Xi Jinping stressed during his speeches at the 17th Academician Conference of the Chinese Academy of Sciences and the 12th Academician Conference of the Chinese Academy of Engineering in 2014 that in the traditional international development arena, the rules have been established by others. China can join the competition, but it must follow the established rules without having any initiatives. To seize the major opportunities from the new round of technological revolution and industrial transformation, China must join the new segments at the initial stage of development, or even lead the development of some segments, so as to make it an important maker of competition rules and an important leader in new arenas.

[26] The NDRC has made several adjustments to the list of strategic emerging industries. For example, it added digital creativity and high-tech service industries.

[27] NDRC (2020). Judgment on the situation of strategic emerging industries and suggestions for the development of the 14th FYP.

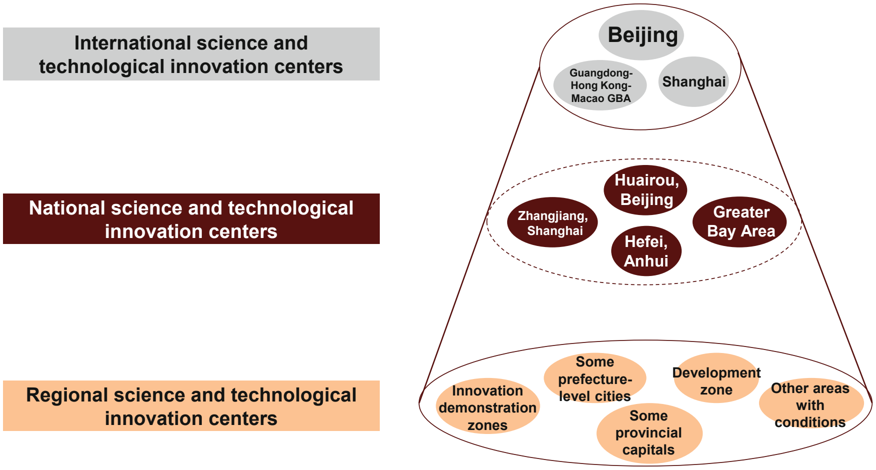

Fig. 7.3 China has built a three-layered innovation system. *Note* The above chart uses 2021 data. *Source* State Council, CICC Global Institute

concentrated in a few countries and regions, due to geographic constraints on knowledge spillover, as well as a virtuous cycle between innovation activities and the concentrations of factors of innovation. In addition, different regional innovation centers compete and collaborate with each other, together promoting the formation and development of a national innovation system.

China has emphasized the development of regional innovation centers. It has built a three-layered system: The first layer consists of international science and technological innovation centers in Beijing, Shanghai and the Guangdong-Hong Kong-Macao Greater Bay Area (GBA). The second consists of national science and technological innovation centers in the Huairou district of Beijing, the Zhangjiang district of Shanghai, and Anhui, Hefei, among others). The third layer consists of regional science and technological innovation centers, including 21 innovation demonstration zones and 169 new national high-tech zones (Fig. 7.3).

Regional innovation centers in China have played an essential role in propelling the construction of the country's national innovation system. Companies in high-tech zones represented around 50% of total R&D investment at companies in China in 2019, accounting for 12% of GDP. In addition, per capita labor productivity in these companies was triple the national average, while their energy consumption per value added was one-third of the national average.[28]

Inspired by the methodology applied by the European Innovation Scoreboard (EIS),[29] we use a five-dimension metric (i.e., research, applications, intermediary

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[28] Source: Highlights in Technological Innovation Underlined by WANG Zhigang, the Minister of Science and Technology issued by China Technology Industry in 2021.

[29] Hollanders, H. (2021). Regional Innovation Scoreboard 2021.

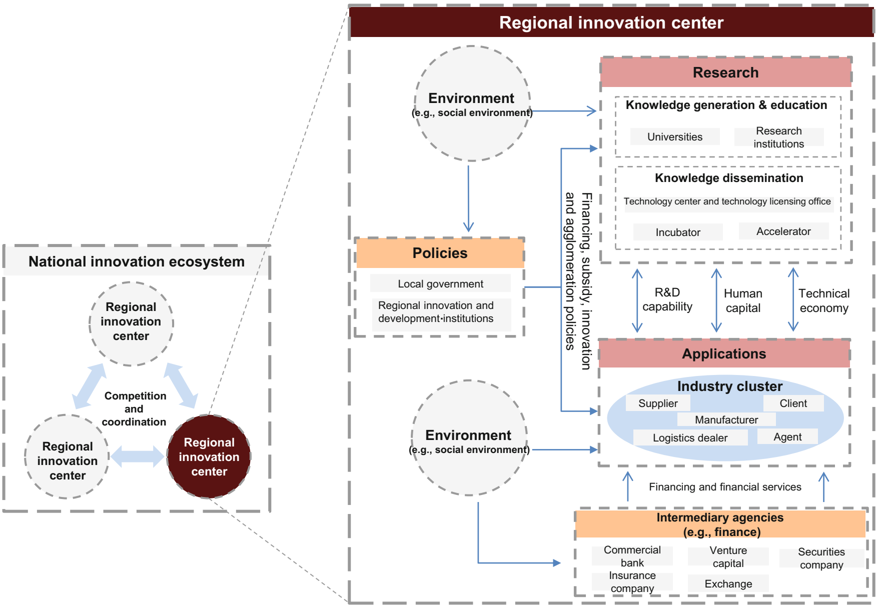

Fig. 7.4 A five-dimension metric to measure development of regional innovation centers. *Source* Autio (1998), CICC Global Institute

agencies, policies, and environment) to measure the development of China's regional innovation centers (Fig. 7.4).

Research: Universities, research institutions, public laboratories, and other organizations dedicated to creating and spreading new knowledge, skills, and technologies play pivotal roles in developing regional innovation centers. We use the number of colleges and universities, the number of research projects, and other indicators to evaluate the capabilities of regional innovation centers.[30]

Applications: A well-built industry chain system not only propels the industrialization and commercialization of innovative products and services, but also plays a crucial role in stimulating innovation. We use the share of companies conducting R&D and the number of high-tech companies, as well as other indicators, to evaluate the applications of innovative products and services in a regional innovation center.[31]

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[30] Indicators to measure the research capability of a regional innovation center include the number of colleges and universities, the number of research projects funded by the National Social Science Fund of China, the number of patents per R&D employee, the number of patent citation, and the number of published papers per R&D employee; source: Ministry of Education, NSFC, local statistical communiques, Innojoy, and Chaoxing Discovery System.

[31] Indicators to measure the applications of innovative products and services in a regional innovation center include R&D expenses at companies above the designated scale as a percentage of total expenses at these companies, R&D employees at companies above the designated scale as a percentage of staff at these companies, companies conducting R&D as a percentage of companies

Intermediary agencies: Financial intermediaries and other agencies provide financing, shared risk, and other services to facilitate innovation activities and propel the application of innovative products and services. We use the number of financial institutions, the value of private equity (PE) and venture capital (VC) investment in the past five years, and other indicators to evaluate intermediary agencies.[32]

Policies: Policies to stimulate innovation vary across regions as different regional innovation centers have different historical backgrounds, natural resources, and industrial structures. We use the number of policies pertaining to innovation, the number of national innovation company incubators, and other indicators to evaluate policies in regional innovation centers.[33]

Environment: The inherent cultural traditions, behavior patterns, and attitudes towards innovation and technological progress greatly affect the development of regional innovation centers. We use the business environment index, the price to income ratio (PIR), and other indicators to evaluate the environment of regional innovation centers.[34]

The five dimensions are not mutually exclusive for building regional innovation centers. For example, universities and companies can cooperate to propel innovation under the R&D contracting model. Companies can also gain knowledge and improve know-how through learning-by-doing, thereby further encouraging innovation.

Based on the five-dimension metric, we conclude the following from our analysis of available data in 49 cities.[35]

Advanced regional innovation centers are concentrated geographically; the innovation indexes of Beijing, Shenzhen, and Shanghai exceed those in other cities. Our metric shows advanced regional innovation centers are concentrated in the Yangtze

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above the designated scale, market cap of listed technology companies as a percentage of GDP, and the number of new and high technology companies; source: local technology bureaus, Wind, local statistical communiques.

[32] Indicators to measure intermediary agencies include the number of banks, the number of securities firms, value of output in the financial industry as a percentage of the GDP, incremental loans as a percentage of the GDP, 5-year PE and VC investment as a percentage of the GDP of the city; source: China City Statistical Yearbooks, Pedata.

[33] Indicators to measure policies in regional innovation centers include government agencies' technology expenditure as a percentage of their total expenditure, government agencies' education expenditure as a percentage of their total expenditure, the number of innovation related policies, the weighted AUM of government-guidance funds, and the number of national innovation company incubators; source: China City Statistical Yearbooks, chacewang.com, Pedata, MIIT.

[34] Indicators to measure environment of regional innovation centers include the digital economy index, the business environment index, the environment and air quality index, the density of road networks, and the PIR ratio; source: White Paper on the Digital Economy Index in China, Management World Economy Research Institution, MEE, China City Statistical Yearbooks, Wind.

[35] The 49 cities include Beijing, Shanghai, Chongqing, Tianjin, Shenzhen, Ningbo, Qingdao, Xiamen, Dalian, Guangzhou, Chengdu, Hangzhou, Nanjing, Wuhan, Xi'an, Zhengzhou, Changsha, Jinan, Hefei, Shenyang, Fuzhou, Shijiazhuang, Guiyang, Nanchang, Nanning, Kunming, Harbin, Changchun, Taiyuan, Urumqi, Lanzhou, Haikou, Lhasa, Hohhot, Yinchuan, Xining, Dongguan, Foshan, Zhongshan, Huizhou, Jiangmen, Zhaoqing, Zhuhai, Jiaxing, Jinhua, Suzhou, Huzhou, Xuancheng, and Wuhu.

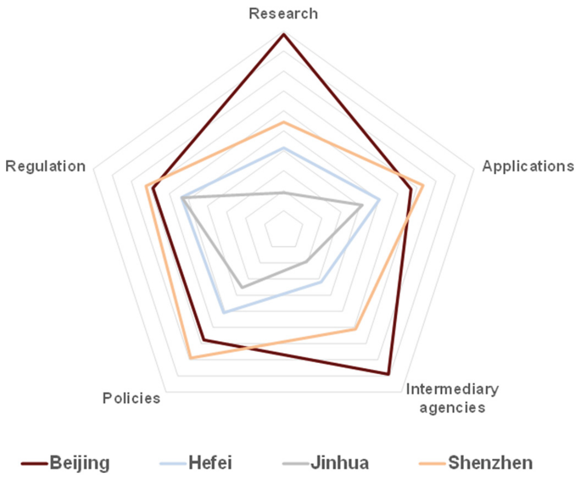

Fig. 7.5 Competitive advantages of four regional innovation centers in 2019. Note: Based on the five-dimension metric system. *Source* CICC Global Institute

River Delta region, the middle and upper reaches of the Yangtze River, and the GBA. Most cities in these regions have high innovation indexes. The indexes of Beijing, Shenzhen, and Shanghai average around 3.5, while those in many provincial capitals are between 1.5 and 2.5.

Regional innovation centers have respective advantages. Different regional innovation centers have different comparative advantages, as shown by our metric (Fig. 7.5). Beijing has higher research and intermediary agency indexes than Shenzhen. However, its application and environment indexes are lower. The innovation indexes of Hefei and other emerging innovation centers are lower than those of Beijing, Shanghai, and Shenzhen. However, they have gained competitive advantages by leveraging research and policy tailwinds.

Jinhua and other manufacturing-oriented innovation cities have lower intermediary agency, policy and environment indexes. However, their application indexes are notably higher, pushing up their overall innovation indexes.

The research indexes are relatively low in many regions, while only a few regional innovation centers have gained advantages in research. Research is one of the main driving forces for innovation, and it is crucial to the development of regional innovation centers. According to our metric, only Beijing, Nanjing, Xi'an, Wuhan, and several cities that are supported by renowned colleges and universities have a relatively solid foundation for research. Innovation capability remains relatively weak in many tier-2 and tier-3 cities.

Networks of Regional Innovation Centers

Cities in the GBA complement each other in innovation activities. The GBA is one of the most innovatively active regions in China. A development situation where cities are complementary to each other's innovation activities has formed there, with Shenzhen and Guangzhou[36] taking the lead in regional innovation activities, and Zhuhai,

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[36] We do not evaluate innovation activities in Hong Kong SAR and Macao SAR, as their data and those of other Greater Bay Area cities are incomparable.

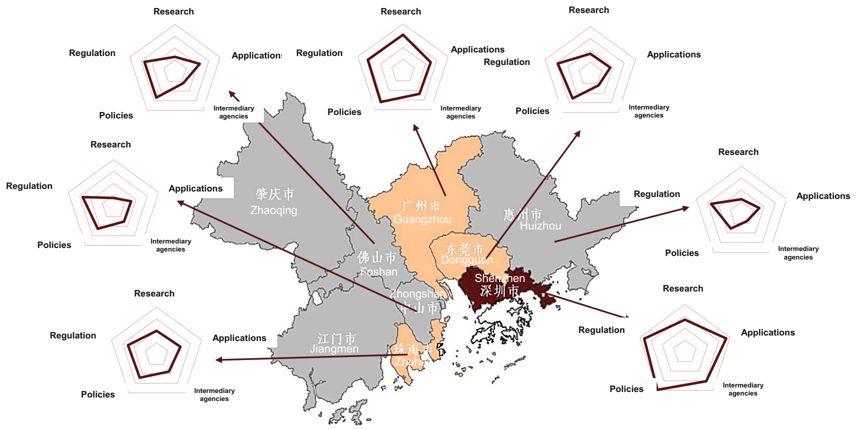

Fig. 7.6 Cities in the GBA area complement each other in innovation activities. *Note* Based on the five-dimension metrics system; we use data for 2019. *Source* CICC Global Institute

Zhongshan, and Huizhou with their respective advantages. Generally, cities in the GBA have notable advantages in applications and environment, but their research and intermediary agency indexes are low. They typically gain advantages from localized manufacturing via industrial transfer, and support the regional innovation network (Fig. 7.6).

The G60 Science and Technology Innovation Valley of Yangtze River Delta to see balanced development of multiple innovation centers. The G60 valley originated in the Songjiang district of Shanghai, and now consists of nine cities in four provincial-level administrative regions, i.e., Shanghai, Jiangsu, Zhejiang, and Anhui. The valley is a multi-layered regional innovation network, with Shanghai leading in regional innovation activities; Hefei, Hangzhou, and Suzhou advancing side by side; and another five cities strengthening their respective capabilities. The innovation indexes of cities in the valley diverge notably, with the innovation index of Xuancheng lower than the indexes of many cities that we monitor. We believe that the cities in the G60 valley will see balanced development of multiple innovation centers, and that the valley will play an exemplary role in propelling innovation in neighboring regions (Fig. 7.7).

Regional innovation centers in China currently confront a number of challenges. First, the guidelines for the development of regional innovation centers could be further clarified. For example, functions and orientations of different regional innovation centers are sometimes overlapping, and the development goals might be unclear. Also, the development of regional innovation centers could be further improved.

Second, divergence in the output efficiency of innovation investments should be resolved. In 2019, technological innovation input and output efficiency (as measured by science and technology expenses and the number of patents at local government agencies) continued to improve in the top 5% of the 100 most advanced cities as measured by GDP in China, while efficiency fell in the top 5–30% of these cities. In 2018 and 2019, the number of patents declined in the remaining cities.

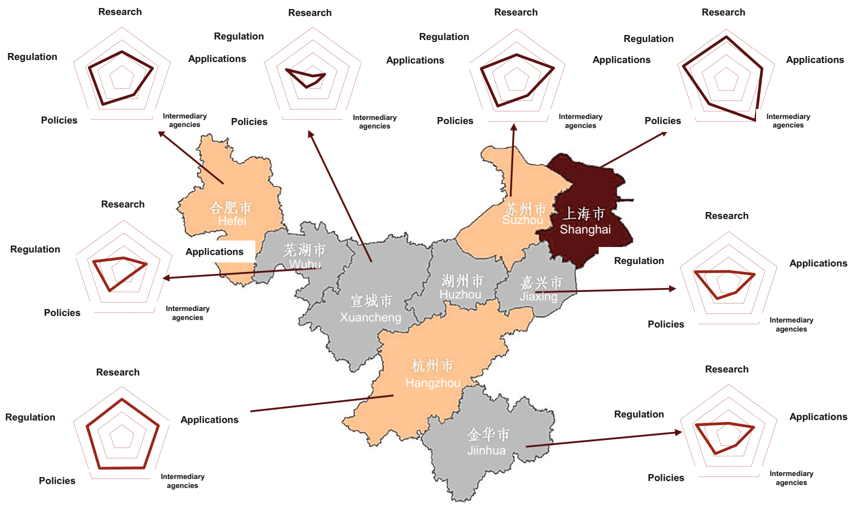

Fig. 7.7 G60 valley to see balanced development of multiple innovation centers. *Note* Based on the five-dimension metrics system; we use data for 2019. *Source* CICC Global Institute

Third, an effective coordination mechanism should be established. Factors of innovation and resources represent the main engine for regional economic growth, in our view. Local government agencies are willing to attract as many innovation resources as possible in order to boost local economic growth. However, from a perspective of the entire country, cross-regional homogeneous competition for innovation resources and repeated investment and construction may, to some degree, impede the completion of a country's innovation targets.

7.2.3 International Experience from Silicon Valley and Germany

National innovation policies and regional resources are crucial to regional innovation centers. Meanwhile, regional innovation centers can facilitate sustainable development of each region and propel innovation in a country.

Silicon Valley is an example of how to build a regional innovation center. Its success could be mainly attributed to the large amount of defense expenditure by the US government during the Cold War period, company strategies, and cooperation between universities and companies.[37]

Silicon Valley's success in innovation is a result of policy support and local advantages. First, R&D contracts signed with the US federal government boosted

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[37] Timothy J. S. (2000) "How silicon valley came to be", in Understanding silicon valley: The anatomy of an entrepreneurial region, Chap. 2, , pp. 15–47.

the growth of start-up firms in Silicon Valley. The value of these R&D contracts exceeded the value of contracts from business customers,[38] and companies undertaking national R&D projects typically received follow-up product orders that gave them opportunities to enter new industries.[39] Second, the rise of high-end electronics manufacturing attracted companies in other regions, raising the concentration of high-tech companies in the region. Third, government agencies generated policies favorable to the VC industry. US Congress approved the Small Business Investment Act and established the Small Business Administration (SBA) in 1958, allowing the VC industry to grow notably in the 1960s. Over the long term, Silicon Valley has accounted for 40% of VC investment in the US.[40]

Long-term growth engines for Silicon Valley include innovation and entrepreneurship friendly environment enabled by human capital, universities, companies. Lenient immigration policies have made Silicon Valley attractive to innovation talent, and helped cultivate a unique innovation culture. This culture has notably improved the efficiency of technological innovation, and was a key competitive advantage for Silicon Valley. Support from universities and alumni associations for innovation and entrepreneurship projects has created a favorable environment for innovation. Leading firms have also been pivotal in cultivating an innovation and entrepreneurship friendly culture.

Silicon Valley continues to eliminate adverse impacts of concentrations of innovation resources. The concentrations of factors of innovation can lead to elevated housing prices, traffic congestion, and other social issues. To solve such problems, cities in Silicon Valley have passed laws to regulate rental prices, thereby avoiding a real estate bubble. At the same time, transport departments have helped alleviate traffic congestion by reducing constraints on infrastructure development across administrative boundaries.

Another example of promoting technological innovation is Germany, which strikes a good balance between cross-regional competition and collaboration. In 1995, the German federal government launched the first national initiative to generate biotechnology clusters, i.e., the BioRegio contest (BRC). Under the BRC program, the federal government chooses several BioRegio to participate. After these regions have formed their own development plans for local biological innovation, an independent review committee selects four winners. The federal government then provides them with funding and policy support, which help increase the R&D capacity of local companies and the industrialization of biotechnology.

The BRC program conducted under the cluster-based model has a clear division of labor that ensures fair and objective results. Second, participants develop their own BioRegio program, which coordinates the government's innovation strategy with the goals of regional development. Such programs promote healthy competition and innovative cooperation among regions. As a result, the BRC program has greatly

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[38] Kenney, M., Florida, R. (2000) Venture capital in silicon valley: Fueling new firm formation, Understanding silicon valley: The anatomy of an entrepreneurial region,

[39] Source: NSF, US Congressional Budget Office.

[40] Source: Thomson ONE, PWC MoneyTree.

improved the division of labor and collaboration between the federal government and the regions, and has played an important role in encouraging innovation.

Germany has notably improved its biotechnology capabilities through the BRC program. The federal government investment in the winning regions has contributed to regional development and an increase in the number of practitioners.[41] Implementing the program has also stimulated the biotechnology industry, with R&D-based clusters emerging, and the number of biotechnology patents in Germany increasing rapidly.[42] Germany continues to support leading biotech firms to sustain the program's achievements and the country's competitive advantage in biotechnologies.

The success of the BRC program demonstrates that the cluster-based model contributes to implementation of a national innovation strategy. Following its success, Germany continues to roll out new cluster-based programs. For example, it proposed the InnoRegio program to address the unbalanced development in eastern and western regions of the country, and the Go-Cluster program to support the transformation of German innovation clusters into international clusters of excellence.[43]

In summary, Germany has built a comprehensive regional innovation center system. The country has conducted multiple innovation programs under a cluster-based model, striking a balance between the federal government and each region, and improving the division of labor, coordination, and cooperation between regions. Follow-up programs have continued to implement the existing innovation strategies amid new trends and innovation needs.

7.3 Government as a Coordinator and Supporter of Technological Innovation

Since China adopted the reform and opening-up policy more than 40 years ago, the country has established a set of innovation systems that conform to its national conditions. However, as China enters a new era of economic development, the *Outline of the 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives* (referred to as the Outline hereinafter) *for 2035* has put forward new goals for China's development in the next 15 years. To achieve the goal of increasing per capita GDP to the level of moderately developed countries by 2035, China's economic growth will rely more on innovation in the context of a decline in working-age population and falling saving rate.

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[41] The value of investment allocated to a region was correlated to the jury's appraisal of this region in the process of preparing for the program.

[42] Dorocki, S. (2014). Spatial diversity of biotechnology centres in germany, Quaestiones Geographicae, (2).

[43] Dohse, D. (2007). Cluster-based technology policy–the german experience, Industry and Innovation, (1).

The Outline puts forward the task of “strengthening original and leading scientific research”, and requires that “basic research accounts for more than 8% of total R&D expenditures” (versus 6% in 2020) and “industrial output of strategic emerging industries accounts for more than 17% of total GDP”. These goals suggest that China will gradually shift its innovation model from “incremental innovation” to “radical innovation”. However, innovation activities in China are still dominated by incremental innovation driven by the commercialization of new technologies, while basic research-based radical innovation activities remain insufficient. The innovation task in the new era poses new requirements for China’s innovation system in terms of both quality and quantity. To fulfill these requirements and correct market failures in R&D, the government’s role in coordinating and supporting technological innovation could not be neglected.

7.3.1 The Government Should Play a Major Role in R&D

7.3.1.1 A “Visible Hand” to Correct Market Failures

We do not think the public sector’s role in R&D should be neglected, although the private sector is now a major source of funding in major economies. Due to the existence of market failures, we believe that the government must play a role as a "visible hand" to boost innovation. The government has various policy options to achieve this.

The first option is to increase the share of government funding in R&D investment. China’s long-term development goals require further increases in R&D intensity and basic R&D investment. Increasing government investment in basic research is a direct solution to China’s insufficient investment in basic R&D caused by market failures. Compared to the US, China’s fiscal R&D expenditures remain low. To achieve long-term development goals, the Chinese government might want to consider increasing the proportion of government funding in R&D investment, especially in basic R&D.

The second is to encourage the private sector to increase R&D investment in radical innovation. In China, the total annual tax credit for R&D expenses of industrial enterprises provided by the government over 2013–2019 climbed from Rmb33.4bn to Rmb140bn, corresponding to an average annual increase of 27%, and its share in total R&D expenses rose to 10% from 4%.[44] An OECD study on effective tax rate for R&D found that the tax rate in China was 11.7% in 2020 versus 20.1% in the US.[45] However, the tax and credit incentives provided by the government for innovative enterprises are not only related to the R&D intensity of the enterprises, but also to their sales revenues and profit. Thus, preferential policies mainly cover

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[44] Source: Statistical Monitoring Report on Innovation Capability of Chinese Enterprises (2020).

[45] Source: OECD Main Statistics of Science and Technology.

incremental innovation related to market development, rather than the basic research vital for radical innovation. The government shall provide additional tax and credit incentives to enterprises focusing on radical innovation, in our view.

The third option is to cultivate long-term investors for innovative activities. Long-term investors in developed economies are usually charitable or pension funds. However, for historical reasons, most pension funds in China still adopt a pay-as-you-go model. With the gradual exit of this model, the balance in individual accounts should gradually increase. This lays a foundation for increasing the number of long-term investors in China's innovation system. The government can also introduce policies to encourage the development of commercial endowment insurance and commercial medical insurance, and encourage qualified enterprises to purchase commercial insurance for their employees. Building China's "third distribution" system, which includes charitable donations, and expanding the scale of endowment and charity funds, should help accumulate funds for long-term investment.

The government could also help establish an innovative intermediary service system to bridge enterprises and universities and thus match technological supply and demand. Such a service system might include, for example, technological transfer offices at research institutions and universities, technology transaction markets, and productivity facilitation centers. In recent years, the Chinese government has launched projects such as the national manufacturing innovation centers, industrial innovation centers, and technology innovation centers. We believe that the government should increase capital and human resource inputs to such bases and centers, driving institutions to play an intermediary role in coordinating cooperation among industries, universities, and research institutes. We believe that this would promote cooperation in innovation activities. Measures could also be taken to reform the education system and transform demographic dividend for talent dividend.

7.3.1.2 Key Periods and Core Industries Need More Government Intervention

The public and private sectors' roles in R&D normally change in the process of national development. First, a country's R&D models vary between different stages of development. They are closely related with a country's stage of development, resource endowment, and policy targets. As short-term focuses differ, policies and R&D models should also be different.[46] To be specific:

For countries experiencing import substitution, such as Germany in the nineteenth century and the US in the nineteenth century and early 2000s, the focus of R&D is technological and product localization, and thus policies should encourage the import and digestion of technology. Government-led R&D, as well as R&D cooperation among companies, universities, and research institutes, are the major R&D models.

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[46] Forbes, N., Wield, D. (2004). What is R&D? Why does it matter? Science and Public Policy, 31(4), 267–277. OECD. (2019). R&D intensity as a policy target: Lessons from 11 international case studies.

For countries that are catching up with advanced economies (such as Germany and Japan after World War II), the focus of R&D is upgrading products and raising international competitiveness. Independent R&D by a company, as well as R&D cooperation among companies, universities, and research institutes, are the major R&D models.

For leading countries, such as the US after World War II and Germany after reunification in 1990, the focus of R&D is on frontier technologies, and cross-country R&D cooperation is needed. In addition to the company-dominated R&D model, government dominance and public subsidies are important R&D models.

Second, the government plays an important role when there are key obstacles to technological development. When a country just starts to catch up with advanced economies or the key obstacles in technological innovation emerge, domestic companies lack enough resources to make breakthroughs, and the government needs to help them overcome these difficulties. When Japan was localizing its semiconductor industry in the 1960s to the 1980s, the country relied on industrial policies to protect the industry when it was in its infancy from being beaten by imports from the US.[47] In 1990, Japan and Germany both faced key obstacles to technological advancement. The governments then reformed R&D systems and started to provide financial support for R&D on clean energy and information technologies.

Third, the government plays a vital role in the forefront of innovations. When technologies and economies are highly developed, innovations would usually enter into uncharted territory, posing strong challenges to R&D. During this time, the boost of technologies to innovations has peaked, and innovations rely more on breakthroughs in basic sciences.[48] Meanwhile, R&D and innovations in uncharted territory are time-consuming and face large uncertainties. Close academic cooperation and opinion exchange through publications (e.g., dissertations) are needed, which has a large knowledge spillover effect that results in market failure. Under these circumstances, the government's role is very important. The US created a number of frontier technology programs after World War II, underscoring the government's role in R&D in uncharted territory.

7.3.1.3 The Policy Options in Favor of R&D

Characteristics of R&D vary among industries, and the government should offer policy support to each industry based on their actual needs. In our view, R&D projects in each industry can be divided according to the time needed and technological complexity.

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[47] Feng, Z.K. (2018). The Catch-up and Innovations of Japanese Semiconductor Industry as well as Thoughts on China's Accelerating Development of Chip Technologies. Japanese Studies 168(06), 5-33.

[48] Rosenberg, N. (1974). Science, invention and economic growth. Economic Journal, 84(333), 90–108.

In terms of the time required, if R&D of a technology is time-consuming and costly, countries that have developed this technology are more likely to maintain their monopoly positions, and other countries would face great difficulties in catching up.[49] In terms of technological complexity, the more complicated a technology is, the more cross-disciplinary expertise its R&D would require, and thus related industries need to spend more time to gain the expertise. In other words, countries that lag in this technology face great difficulties in catching up.

For industries that are relatively less complicated and have a shorter R&D cycle, leading countries could only succeed in restricting others in the short run. The problem for lagging countries is how to mobilize capital and human resources to support the costly and time-consuming R&D of frontier technologies. In this context, we believe the government should encourage the private sector to invest in R&D; support cooperation among companies, universities, and institutes; and increase R&D spending on the industries mentioned above.

However, for technologically complicated industries with a long R&D cycle, companies themselves are not capable enough to make R&D breakthroughs in the short term, and hence governments need to play a major role. For example, the Japanese government played an important role in helping its semiconductor sector catch up with foreign competitors in the 1960s and 1970s. The German government also helped its chemical sector catch up in the nineteenth century. We believe the R&D policy options for these industries with complicated technologies include:

The government needs to increase R&D spending; promote R&D cooperation among companies, universities, and public research institutes; and mobilize each party to make breakthroughs. In our view, R&D of crucial industrial technologies, especially of general-purpose technologies, requires the government to function as a coordinator. We think the government should spend more on R&D; encourage eligible companies to make breakthroughs; and define the public sector and the corporate sector's roles, liabilities, and interests regarding joint R&D and independent R&D. For instance, Japan established a sizable integrated circuit (IC) institute to support its semiconductor industry,[50] which we believe is a typical case of the government's participation in R&D of crucial technologies. In our view, the Chinese government needs to play a role to promote R&D cooperation in key areas such as IC equipment, aircraft engines, and high-end precision instruments.

The government also needs to cultivate innovative talent and help universities and research institutes boost R&D capabilities. To realize this goal, we think the government should cultivate local scientists, engineers, and technicians, and attract foreign talent at the same time. For instance, the rise of Germany's machinery and chemical industries relied on a large number of workers from the UK,[51] including German

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[49] Zeng, F.H., Zhao, Z.Y., Jiang, Y.S. (2013). Studies on Industrial Technology Monopoly and Competitiveness. Management World (1): 180-181.

[50] Feng, Z.K. (2018). The Catch-up and Innovations of Japanese Semiconductor Industry as well as Thoughts on China's Accelerating Development of Chip Technologies. Japanese Studies 168(06), 5-33.

[51] Freeman, C., Soete, L. (1997). The economics of industrial innovation (3rd ed.). Wellington House.

students who studied in the UK. In addition, the prosperity of the German chemical industry, to a large extent, is attributable to the extensive cooperation between domestic universities and large companies such as BASF and Bayer.[52] We believe this underscores the importance of R&D cooperation between companies and universities or research institutes.

7.3.1.4 The Government Could Enhance the Efficiency of Financial Support for R&D in the Private Sector

If the government's financial support for R&D prompts the private sector to increase R&D spending, we believe this would be more beneficial than simply increasing public spending on R&D. Empirical studies suggest that the government's financial support for R&D would stimulate corporate spending on R&D. Nevertheless, the effect of any support tends to vary, depending on four criteria.

Business size: For smaller firms, the government's financial support for R&D is helpful, and can have a greater effect than supporting larger companies.[53]

Development stage: Startups typically lack resources, and the government's financial support for their R&D can help produce better outcomes. In contrast, financial support for mature companies is unlikely to generate desirable effects.[54]

R&D intensity: The higher R&D intensity a company has, the stronger its technological strength, and the better results of the government's financial support. However, when a company's R&D intensity reaches a sufficient level, the marginal effect of financial support diminishes.[55]

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[52] Source: BASF's website. Freeman, C., Soete, L. (1997). The Economics of Industrial Innovation (3rd ed.). Wellington House.

[53] Li, Y., Meng, X.Y., Wang, Y.P. (2014). The Government's R&D Financial Support and Corporate Technological Innovations: Empirical Studies based on Multi-dimensional Industrial Heterogeneity. Science of Science and Management of S.&.T. 35(1): 33-41. Gonzalez, X., Pazo, C. (2008). Do public subsidies stimulate private R&D spending? Research Policy, 37(3), 371–389.

[54] Xiong, H.P., Yang, Y.J., Zhou, L. (2016). The Impact of Government Financial Support on Companies in Different Life Cycles. Science of Science and Management of S.&.T., 37(9), 3-15.

[55] Bai, J.H., LI, J. (2011). The Government's R&D Financial Support and Corporate Technological Innovations: Empirical Studies based on Efficiency. Journal of Financial Research (6), 181–193; Li, Y., Meng, X.Y., Wang, Y.P. (2014). The Government's R&D Financial Support and Corporate Technological Innovations: Empirical Studies based on Multi-dimensional Industrial Heterogeneity. Science of Science and Management of S.&.T. 35(1): 33-41; Radas, S., Anić, I.-D., Tafro, A., Wagner, V. (2014). The effects of public support schemes on small and medium enterprises. Technovation; Li, R.Q., Bai, J.H. (2013). The Impact of Government Financial Support on Corporate Innovations: Empirical Studies based on Threshold Regression. China Economic Studies (03), 13-25.

Type of ownership: Multiple empirical studies show the Chinese government's financial support cannot significantly boost R&D spending and efficiency of SOEs, but the effect on other types of firms is highly positive.[56]

In addition, policy tools can also affect the results of financial support for R&D. Tax allowances are a popular tool used by governments to encourage companies to increase spending on R&D. This is particularly the case for high-tech firms, smaller companies, and firms that have not invested greatly in R&D. However, unlike direct subsidies, tax allowances prompt companies to pursue R&D projects that may generate lucrative profits in the short term rather than focusing on long-term basic research. Moreover, if a company's taxes are minimal pre-allowance, the impact of any additional tax allowances would be relatively low.[57]

Credit policies are also used as complementary policy tools for R&D. Compared to direct financial support, supportive credit policies can reduce moral hazard as loans need to be repaid. Studies show that supportive credit policies such as subsidized loans can promote corporate R&D, while direct subsidies cannot produce the same results. The effect of subsidized loans in regions with poor financial conditions tends to be much greater than in other areas.[58]

The scale of the government's R&D financial support, selection of qualified parties qualified for the support, stability of the support, and how government funds are utilized can also affect the result of the financial support.[59] Studies show that R&D

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[56] Bai, J.H., LI, J. (2011). The Government's R&D Financial Support and Corporate Technological Innovations: Empirical Studies based on Efficiency. Journal of Financial Research (6), 181–193; Li, Y., Meng, X.Y., Wang, Y.P. (2014). The Government's R&D Financial Support and Corporate Technological Innovations: Empirical Studies based on Multi-dimensional Industrial Heterogeneity. Science of Science and Management of S.&.T. 35(1): 33-41; Li, R.Q., Bai, J.H. (2013). The Impact of Government Financial Support on Corporate Innovations: Empirical Studies based on Threshold Regression. China Economic Studies (03), 13-25; Pan, L., Li, Z.P. (2020). Did Government Subsidies Prompt Manufacturers to Increase R&D Spending? Reform of the Economic System, No.221(02), 113-120.

[57] OECD. (2020). The effects of R&D tax incentives and their role in the innovation policy mix: Findings from the OECD microBeRD project, 2016–19; Jun, W. (2011). Estimated intensity and impact of chinese tax allowance on R&D, Science Research Management, *32*(9), 157–164; Becker, B. (2015). Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence. Journal of Economic Surveys, 29(5), 917–942; Ozçelik, E., Taymaz, E. (2008). R&D support programs in developing countries: The Turkish experience. Research Policy, 37(2), 258–275; Radas, S., Anić, I. D., Tafro, A., Wagner, V. (2015). The effects of public support schemes on small and medium enterprises. Technovation, 38, 15–30.

[58] Li, X.G. (2016). Government Financial Support for R&D, Financial Credit and Corporate Technological Innovations, Management Review, 28(12), 54-62; Zhang, J., Chen, Z.Y., Yang L.X., Xin, F. (2015). Evaluation of China's Innovative Subsidy Policies. Economic Research Journal 10, 4–17.

[59] Becker, B. (2015). Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence. Journal of Economic Surveys, 29(5), 917–942; Görg, H., Strobl, E. (2007). The effect of R&D subsidies on private R&D. Economica, 74(294), 215–234; Li, P., Wang, C.H. (2010). Non-linear Studies on Impact of Government Funding Support on Corporate Technology Innovations. China Soft Science (8), 138-147; Dai, X.Y, Cheng, L.W. (2014). Threshold Impact of Fiscal Subsidies on Corporate R&D Spending. Science Research Management 35(006), 68-76; Liang, J., Fiorino, D. J. (2013). The implications of policy stability for renewable energy innovation in the United States, 1974-2009. Policy Studies Journal, 41(1), 97–118; Foray, D., Mowery, D.

financial support does not produce good results if the scale is too large or too small. Offering moderate financial support to many companies may be more beneficial than providing strong funding support to a few companies. Enabling companies to receive gradual, predictable, and reliable R&D funding support is better than offering funding support ad hoc, as indicated by empirical studies on technological innovation in energy.

In addition, competitive R&D subsidy policies can help companies enhance innovation efficiency. Against the background of accelerating "radical innovation", China's innovation system has shortcomings. The most prominent issues include a lack of impetus for basic scientific research and innovation, support from the education system to develop human resources capable of innovation, and the government's need to improve its innovation governance capability.

7.3.2 Improving Innovation Governance Capability: Scientific Decision-Making and Flexible Management

Given the strategies introduced in this new era, the Chinese government has an urgent need to improve its innovation governance capability. A primary task is to make the decision-making process more "scientific". A basic principle of technological innovation and industrial development is that enterprises of different types and scale and in different segments play specific roles, forming an industrial system featuring market-based operations, with the market economy and enterprises as the core actors within the system.

However, some policies introduced at local levels are not based in science. For example, the industrial planning and policies adopted in different regions are highly similar, resulting in overcapacity or even abandoned projects. Supportive policies tend to favor large or renowned companies, while SMEs contributing to technological innovation can only access limited resources, which does not bode well for the improvement of the regional innovation system. Moreover, due to insufficient understanding of the complexity of industries and their feature as a system, supportive government policies for industries often fail to deliver desired results.

Another mission is to increase the flexibility of R&D management system. China's R&D management system features regulatory planning and administrative interventions. Some of the departments involved might not fully recognize the diversity of human capital, lack of consensus, and uncertainty in scientific research. This undermines China's ability to achieve a flexible management structure or to adopt a scientific and reasonable method of resource allocation. These problems may dampen the motivation of talented individuals, especially young people, and are detrimental to a research culture that features free thinking and the pursuit of excellence.

C., Nelson, R. R. (2012). Public R&D and social challenges: What lessons from mission R&D programs? Research Policy, 41(10), 1697–1702; Colombo, M. G., Grilli, L., Murtinu, S. (2011). R&D subsidies and the performance of high-tech start-ups. Economic Letters, 112(1), 97–99.

Given the new tasks in the new era, we suggest that the government strengthen its innovation governance capability and introduce more policies based on scientific decision-making. Some solutions might include the following.

Mission-oriented approach. Local governments determine their technological innovation missions in accordance with the central government's strategic deployment and regional development plans, and formulate policies accordingly after clarifying the major tasks.

Forward-looking research. When formulating technological innovation policies, related departments need to conduct extensive research first, and introduce and implement policies after gaining a good understanding of market trends, corporate needs, and how the policies work and take effect.

Leveraging market resources, with the market serving as a tool to improve policy efficiency.

The market provides abundant information, which is conducive to the formulation and implementation of government policies. The market also provides a variety of resources, and the government can use the resources at hand to leverage more market resources so as to achieve innovation-related goals and tasks.

7.3.3 Promoting Innovation Through the New System for Mobilizing Resources Nationwide

The system for mobilizing resources nationwide, known by the abbreviation SMRN, refers to an innovation policy model which establishes a special organization to mobilize resources within a short period in order to quickly achieve a strategic goal.[60] From the perspective of institutional economics, transaction costs are the core factor affecting economic entities. The SMRN greatly reduces internal costs through a state-led approach, and the government coordinates the implementation of market institutions to reduce uncertainty. The problem of insufficient innovation incentives caused by market failures can also be corrected.

When the People's Republic of China was established, in order to develop its industrial sector against the background of the blockade by Western countries, China introduced a nationwide system of "concentrating resources to accomplish major undertakings" in the industrial sector.

Market-oriented Western economies such as the US and EU established similar institutions when they had to channel a large amount of resources to complete major goals. For example, institutions such as the War Production Board (WPB), the Manhattan Engineer District, and the Defense Advanced Research Projects Agency (DARPA) existed in the US since the middle of the twentieth century. During the technology innovation boom in the 1980s, the US established departments such as the Small Business Administration (SBA), the Department of Energy

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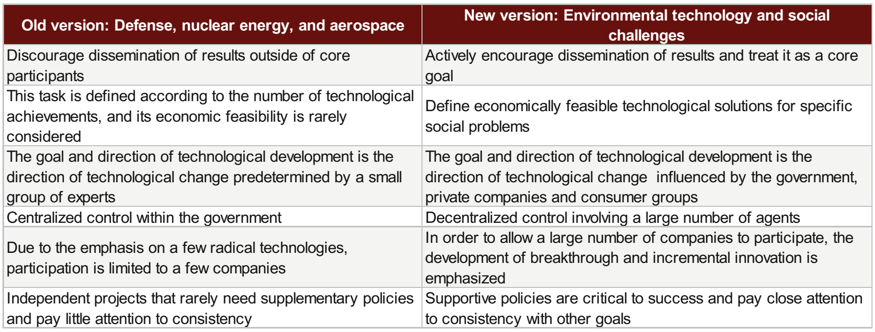
[60] Chen, J., Yang, Z., Zhu, Z. (2021). The theoretical logic, implementation mode and application scenario of the new type of national system. Reform. (5): 1–17.



Old version: Defense, nuclear energy, and aerospace	New version: Environmental technology and social challenges
Discourage dissemination of results outside of core participants	Actively encourage dissemination of results and treat it as a core goal
This task is defined according to the number of technological achievements, and its economic feasibility is rarely considered	Define economically feasible technological solutions for specific social problems
The goal and direction of technological development is the direction of technological change predetermined by a small group of experts	The goal and direction of technological development is the direction of technological change influenced by the government, private companies and consumer groups
Centralized control within the government	Decentralized control involving a large number of agents
Due to the emphasis on a few radical technologies, participation is limited to a few companies	In order to allow a large number of companies to participate, the development of breakthrough and incremental innovation is emphasized
Independent projects that rarely need supplementary policies and pay little attention to consistency	Supportive policies are critical to success and pay close attention to consistency with other goals

Fig. 7.8 Comparison between versions of the SMRN. *Source* Mazzucato (2017), CICC Global Institute

(DOE), and the Department of Transportation (DOT) to implement projects aimed at supporting SMEs, such as Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR) and Small Business Investment Company (SBIC) programs.

The new SMRN emphasizes the application of the system to innovative tasks in the field of environmental protection and social reform, as well as the resulting change in the relationship between the government and the market. The concept of "mission-oriented" innovation proposed by Italian academic Mazzucato[61] clarifies that the role of government as not only intervening when there are explicit market failures, but also to co-create and shape markets. For example, the Chinese government led the development of a green economy and introduced the goals of reaching peak carbon emissions and achieving carbon neutrality, which triggered the need for technological innovation, and further led to the launch of voluntary emissions reduction projects similar to Alipay's Ant Forest.[62] These moves to guide market participants to invest in innovation and achieve established strategic missions are features of the new SMRN (Fig. 7.8).

The green economy helps fuel SMRN. Compared with the SMRN that supported high-tech industries in the 1970s and 1980s, a similar model is needed to drive a disruptive green revolution. In the US, President Joe Biden's US$1.2trn Infrastructure Investment and Jobs Act provides investment in electric vehicles, clean energy, broadband, and power grids exceeding US$120bn. Green transition is also at the core of the EU's economic recovery plan issued at the end of 2020. The EU introduced the Next Generation EU recovery instrument with total investment of EUR1.8trn, with

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[61] Mazzucato, M. (2017). Mission-oriented innovation policy. In UCL institute for innovation and public purpose working paper (Issue 1).

[62] Ant Forest is a public welfare initiative designed by the Ant Group in the Alipay to create a carbon account for Chinese users, which launched in August 2016 and won a UN "Champions of the Earth Award". Users can raise a virtual tree in Alipay by walking, traveling on the subway, paying utility bills online and other emission reduction behaviors. As the "tree" grows, public welfare organizations, environmental protection enterprises, and other partners "buy" the user's "tree" and plant a real tree.

37% of the funds to be invested in green transition and innovation in related fields.[63] YI Gang, the former governor of the People's Bank of China (PBoC), predicted that China's low-carbon economic strategy would drive investments in the tens of billions of renminbi in related fields between 2021 and 2050.[64]

7.3.4 National Innovation Systems: The US Experience

Well-coordinated and orderly organizational structure at the federal level are distinguishable features of the US innovation system. The US federal government has three layers of administrative departments to formulate policies and organize innovation networks.

The first layer comprises organizations and institutions under the White House. By setting up institutions including the Office of Science and Technology Policy (OSTP), the National Science and Technology Committee (NSTC), and the President's Council of Advisors on Science and Technology (PCAST), the White House integrates the three functions of administration, decision-making and coordination, and professional consultation. This allows the US to establish a top-level governance mechanism for technological innovation.

The second layer comprises relevant administrative departments, with each department having an independent financial budget to support R&D activities in their respective fields. The Department of Defense, the Department of Health and Human Services, and the Department of Energy accounted for the largest share of the total budget over the years, which shows that the US attaches great importance to the military, medicine, and energy technology industries.

The third layer includes the special research institutions under the administrative departments, which are responsible for allocating the R&D budgets of the corresponding departments to various institutions across the country, with part of the fixed budget allocated to research centers and entities under the institutions to undertake research projects directly. Such a mechanism ensures that the country's R&D funds are mainly allocated by professionals.

At the same time, non-market based policies enable the visible hand to play a key role. By adopting the so-called "non-market based" policies, the government does not selectively fund certain industries or institutions based on market mechanisms. Besides taking the form of top-down, command-based planning, such policies could also be adopted under the model of developmental network state, giving a boost to technological innovation.[65]

The US federal government's R&D subsidy and consortium policies are typical non-market based policies. The R&D subsidy policy is implemented via a variety of

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[63] The EU promotes green economic growth, Xinhuanet.com, November 16, 2020.

[64] YI Gang's speech at the roundtable of China Development Forum 2021.

[65] Block, F. (2008). Swimming against the current: The rise of a hidden developmental state in the united states. Politics & Society, *36*(2), 169–206.

technology programs. For example, government departments also review the application submitted by market institutions, and offer support to high-quality ones. In addition to sector-specific support, the federal government also supports cross-sectoral technology programs.

The US government also influences development of technological innovation through non-market based investment and trade policies and antitrust policies, among others. The US strictly reviews the acquisition of US companies by foreign entities on the grounds of national security. Meanwhile, the Department of Commerce oversees the export of US technologies, and selectively reviews and supervises export activities to certain countries. Antitrust policies have an important impact on the landscape of the US technology industry. For example, the tightening antitrust measures over 1940–1980 resulted in relatively loose intellectual property rights protection, which in turn promoted the growth of emerging enterprises in the early stage.

In addition to non-market based measures, the US government implemented a series of market-based policies to encourage innovation. The so-called market-based mechanism refers to policies that cover all market entities and do not hinder the operation of the market mechanism. As long as related conditions are met, all innovative entities would receive policy support.

In terms of R&D policies, in addition to launching selective technology programs, the federal government introduced universal R&D tax credits in 1981, followed by various states from then on. So far, more than 30 states have adopted this policy.[66] The policy has been widely applied in OECD countries and has been proven effective in increasing corporates' R&D investment (for details, please refer to Chap. 1).

The US has established a sound intellectual property system. Strengthening the protection of patent rights makes it easier for new companies with only a few patents to enter the market with technological strength. It also promotes the vertical division of labor among technology companies, especially in the field of biomedicine. [67] The US has also introduced a number of laws to ensure the smooth progress of technology transfer, thereby protecting the due rights of R&D personnel and promoting enthusiasm for innovation.

In the field of finance, the US government launched a special policy. Specifically, it introduced a special venture capital license under the SBA, so as to promote the development of the venture capital industry in the US. In addition, the US adopts a looser stance on immigration policy, which enables the country to attract a large number of foreign students and scholars to visit or study in the US. This provides an important talent supply mechanism for innovation activities in the US.[68]

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[66] Wilson, D. J. (2009). "Beggar thy neighbor? The in-state, out-of-state, and aggregate effects of R&D Tax Credits." Review of Economics and Statistics, 91 (2): 431–436.

[67] Mowery, D. C. (2009). Plus ca change: Industrial R&D in the "third industrial revolution." Industrial and Corporate Change, *18*(1), 1–50.

[68] Bryan, K. A., Williams, H. L. (2021). Innovation: Market failures and public policies. In NBER Working Papers, 29173.

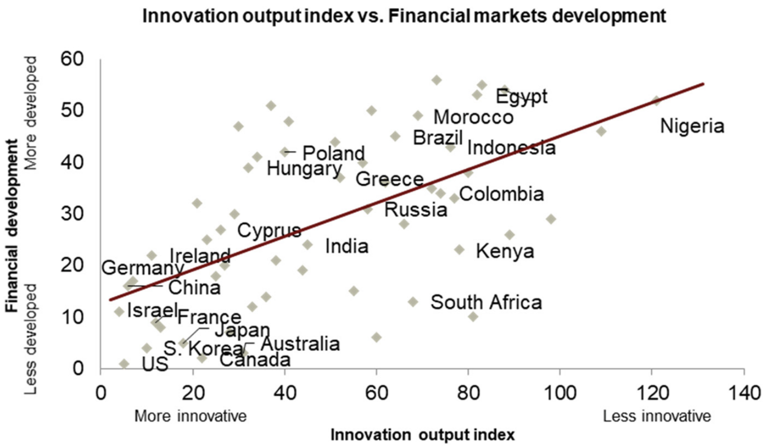

Fig. 7.9 Finance and innovation are positively correlated. *Note* The financial market development index is a financial industry index that the CICC Global Institute compiled based on credit, market capitalization, and venture capital deals in each country that the Global Innovation Index (GII) covers; the GII measures global ranking based on scientific knowledge output and innovation output (including intangible assets, creative goods and services, and online creativity). *Source* Global Innovation Index 2020, CICC Global Institute

7.4 Financing innovation—Capital Markets Are Not The Only Player

Financial support is the backbone of technological innovation. As mentioned previously, financial support is a framework condition for promoting innovation. Statistics also show that finance and innovations are positively correlated (Fig. 7.9). How might we interpret any causal relationship? Does finance lead to innovation (or vice versa), or are finance and innovation both triggered by other factors? What is the most effective way to finance innovation? This section discusses the relationship between finance and innovation, how different financial structures support innovation, and government's role in financing innovation.

7.4.1 The Financial Industry Does not Spontaneously Invest in or Promote Innovation

As mentioned in the previous section, innovation has positive externalities, and results of innovation are highly uncertain. We believe this explains why the financial industry neither spontaneously invests in innovation (although it can support innovation) nor spontaneously promotes innovation (though innovation requires financial support).

The financial industry does not spontaneously invest in innovation. Financial firms and industrial companies both seek to maximize profit. They lack a strong desire to support innovation if other activities prove more profitable, in our opinion. A large number of economic activities are highly profitable, and their existence is necessary; thus, it is reasonable for the financial industry to support these activities.

In contrast, housing market speculation exhibits negative externalities, with the resulting financial risk being borne by the whole country and returns being owned by individuals. As such, we believe it is unreasonable to use ample financial resources to support these activities. Studies show that housing price bubbles can significantly constrain innovation in the real economy.[69]

Some innovation activities are not highly cost effective, which is another reason why financial companies lack a strong desire to invest in innovation. There are great uncertainties in technological innovation, and the probability of failure is relatively high. Also, the "innovation paradox" theory means innovation activities may not necessarily become more cost effective even if R&D proves successful. According to this theory, if innovation-driven companies do not innovate, market demand will shrink and they will lose their market positions. However, if they push ahead with innovation, their market positions may be threatened by their own innovation. This helps explain why innovation-driven companies are not as long-lived as other firms. The high probability of failure for innovation activities makes cash flow less predictable, and reduces the likelihood of being profitable. The innovation paradox shortens the expected lifecycle of innovative firms. These two factors both make innovation investment less attractive.

The financial industry is unlikely to promote innovation spontaneously. Research suggests the financial industry can guide innovation,[70] accelerate it,[71] be neutral towards it,[72] and also constrain it,[73] depending on the circumstances. The divergence implies that financial resources do not spontaneously promote innovation even if they are used to fund innovation. The reason is easily understood. Financial firms seek to make a profit, which might be incompatible with the target of corporate innovation. In addition, they may stop relying on promoting innovation to make money if they find innovative companies can help them earn more by improving financial indicators and taking other actions rather than by increasing R&D spending, in our opinion.

However, most studies generally hold neutral or positive views towards the impact of financial resources involved in innovation. Although a popular view argues that innovation should rely on capital markets funding instead of bank credit, leaders at tech firms such as Tesla[74] would appear to disagree with this view.

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[69] Miao, J., Wang, P. (2012). Sectoral bubbles and endogenous growth, department of Economics.

[70] Chowdhury, R. H, Min, M. (2012). Financial market development and the effectiveness of R&D investment: Evidence from developed and emerging countries, Research in International Business and Finance.

[71] Some have disputed this conclusion (Hsu P H, Xuan T, Yan X, 2014; Nanda R, Rhodes-Kropf M, 2017).

[72] Guo, D., Jiang, k. (2013) Venture capital investment and the performance of entrepreneurial firms: Evidence from china, Journal of Corporate Finance.

[73] Hsu, P. H., Xuan, T., Yan, X. (2014). Financial development and innovation: Cross-country evidence, Journal of Financial Economics.

[74] https://www.tesla.com/blog/taking-tesla-private.

Overall, a popular view holds that supporting innovation relies on capital markets instead of bank credit. In contrast, leaders of top-tier high-tech firms are negative on the capital market's impact on innovation, and opt to embrace bank credit. To understand these two different opinions, we analyze the relationship between finance and innovation from the perspective of financial structure in the following section.

7.4.2 *Financial and Innovation Structure: 'Catching up' Innovation Model and 'Leading' Financing Model*[75]

In our view, it would be unfounded to say that supporting innovation requires capital markets instead of bank credit, but rather both are needed. We do not believe banks' potential support for innovation should be neglected. As we stated earlier, a popular view holds that supporting innovation relies on capital markets instead of bank credit. However, this view considers only financial structure, and neglects the structure of innovation. The roles of capital markets and bank credit in promoting innovation are different, and cannot be replaced by each other. When understanding their roles, we think types of innovation should be taken into consideration. In particular, large companies lack a strong desire for radical innovation, and prefer incremental innovation. In contrast, smaller companies prefer to promote radical innovation as they face lower costs when pushing it. We believe they are more willing to, and more capable of, relying on radical innovation to challenge larger companies' dominant positions. In their early stages, mid- and small-sized firms rely heavily on the private equity market, where financial resources are limited and risks are relatively high. In contrast, banks with ample financial resources and low-risk appetite prefer mature and large companies. Thus, we can conclude that the capital market is more helpful in promoting radical innovation, while bank credit is more effective in pushing incremental innovation.

However, incremental innovation and radical innovation are not mutually exclusive; instead, these two types of innovation are closely related in many cases. In fact, incremental innovation paves the way for radical innovation, while the latter creates more opportunities for the former. They can both generate important social implications due to their dialectical relations. In our view, the importance of two innovation-financing models differs in different stages of economic development. For lagging countries that are catching up with leading ones, the main purpose of innovation is to help the former more quickly accomplish the stages of development completed by the latter. Under such circumstances, the bank-dominated innovation financing model helps mobilize resources to accelerate incremental innovation, catch up with

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[75] In this report, the "catching up" innovation financing model refers to the innovation financing model where large banks offer ample credit resources to big companies to promote incremental innovation. The "leading" financing model is the innovation financing model where mid- and small-sized companies use the money from capital market to fund innovation. This model may help China become a global frontrunner in technological advances.

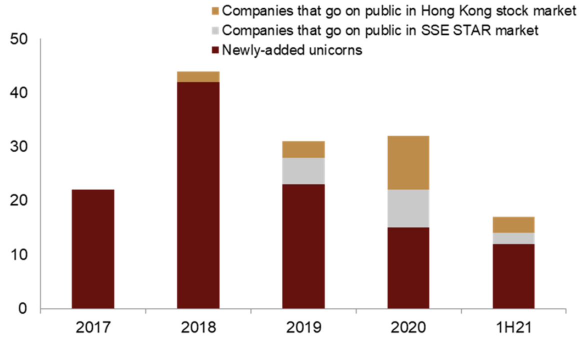

Fig. 7.10 Number of new unicorns after excluding the impact of new listing rules. *Source* CB Insights, Wind, CICC Global Institute

advanced economies, and eliminate the vertical risks to domestic value chains, in our opinion. For leading economies, their leadership can be characterized by radical innovation such as ample new products and philosophy. Their capital market needs to play a more important role than bank credit in innovation funding.

Currently, China is catching up with advanced economies and may become a global technological frontrunner in the long term, in our view. Some domestic segments such as semiconductor are facing vertical risks. In these segments, the "catching up" innovation financing model in which large banks offer ample credit resources to big companies may need to play an important role, in our view. As such, China should improve the "leading" innovation financing model in which mid- and small-sized companies rely on capital markets to raise money to fund innovation. In our view, given the current environment of industrial security, it is necessary to analyze capital market and bank credit's relationships with radical and incremental innovation.

7.4.2.1 The Private Equity Market Faces Challenging Transformation

After rising annually before 2018, the number of new unicorns in China has plunged (Fig. 7.10). The number has contracted since 2018, even excluding the impact of HK IPO system reform in 2018 and the launch of the SSE STAR market in 2019. The private equity market faced transformation challenges in fundraising and investment in recent years. We believe this contributed to the decline in the number of unicorns in China.

Private equity market's transformation in financing model amid new asset-management regulation. The total size of fundraising by Chinese VC funds is similar to the volume seen in the US (Fig. 7.11). For instance, Chinese VC funds combined raised about US$70bn in 2020, compared with US$79.8bn in the US.[76] Fundraising size in the US expanded steadily in the past decade, while the size in China lost steam after peaking in 2018.

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[76] Source: Pedata, NVCA.

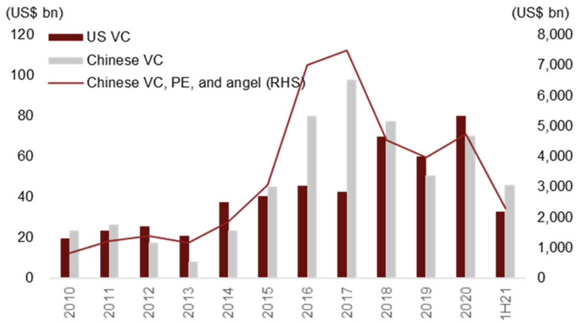

Fig. 7.11 Size of fundraising by Chinese VC funds was similar to the volume in the US, but growth has remained soft in recent years. *Source* Pedata, NVCA, CICC Global Institute

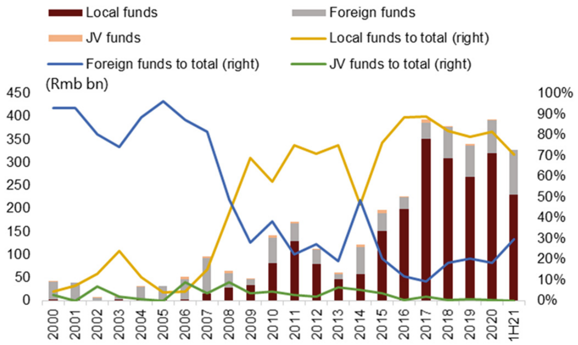

Fig. 7.12 Fundraising sources of Chinese VC funds. *Source* Pedata, CICC Global Institute

Chinese investors replaced foreign ones as the largest capital source of Chinese VC funds after 2007 (Fig. 7.12). However, the share of Chinese investors started to shrink after reaching 89% in 2017. In contrast, the share of foreign investors and their total investment in Chinese VC funds both trended upward after 2017. We believe this trend also means Chinese VC funds' soft fundraising volume growth in 2018–2020 is mainly due to issues relating to domestic investors.

From 2018 to 2020, the new asset-management rules[77] have not only effectively clamped down on improper financial actions but also pushed VC firms to change their fundraising methods and face high latent financial risks. These new rules have largely prevented managers of publicly-offered asset management products from investing in institutions that focus on investment in unlisted shares. As shown by the limited partnership structure of funds that invest in unlisted shares, their funds from financial institutions plunged since 2018 (Fig. 7.13).

Internet regulation pushed VC firms to shift the focus of their investment to the technology sector. The fundraising pressure naturally affected VC firms' investment. Chinese VC companies hold their investment projects, on average, for only 3.3 years,

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[77] On April 27, 2018, the People's Bank of China, China Banking and Insurance Regulatory Commission, China Securities Regulatory Commission, and State Administration of Foreign Exchange jointly issued a guideline on financial institutions' asset management business.

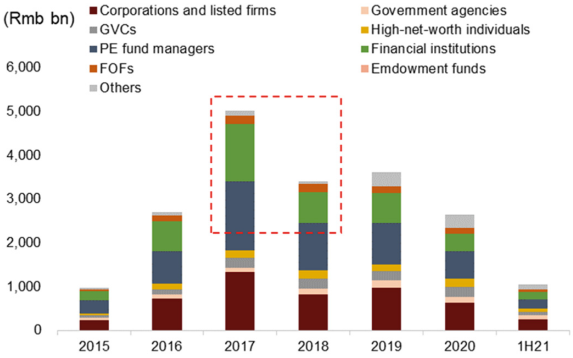

Fig. 7.13 Limited partnership (LP) structure of funds that focus on investing in unlisted firms. *Source* Pedata, CICC Global Institute[78]

compared with 8.2 years by their US counterparts[79] (Fig. 7.15). The shorter holding period indicates that Chinese VC firms are not highly tolerant of innovation failure, in our view. However, we believe tolerating short-term failure and providing an impetus to long-term innovation happen to be the most effective way to stimulate innovation.[80]

We believe Chinese VC firms need to change their traditional investment style. Internet regulations are increasingly strict, with China clamping down on the monopoly of e-commerce platforms, and the country has intensified oversight of online education. Some VC firms switched to traditional consumer areas with lower risks (e.g., hand-pulled noodles and cakes). Other VC companies shifted to Chinese segments that face vertical risks such as software, biotechnology and semiconductors. In our view, these moves indicate that VC firms' propensity to invest has not declined despite the pressure for investment style transformation. This trend also echoes our view that financial firms and even VC companies do not spontaneously invest in or promote technological innovation (Fig. 7.14).

7.4.2.2 The Stock Market: Creating Sound Exit Channels for VC Firms is Key

Although we believe the stock market is less effective than the private equity market in promoting radical innovation, it nevertheless plays an important role in the process. We believe the key is building sound exit channels for investors in the private equity market. In order for capital markets to promote radical innovation, the private equity and stock markets both need to play their roles. In the US, IPOs represent the most important exit channel for VC firms in terms of the aggregate value of the projects

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[78] The funds include angel, VC and PE funds; financial institutions include securities firms, trust institutions, banks, insurers, investment firms, and asset management companies.

[79] Pitchbook, The Handbook of China's Financial System, 2017.

[80] Manso, G. (2011) Motivating innovation, Journal of Finance.

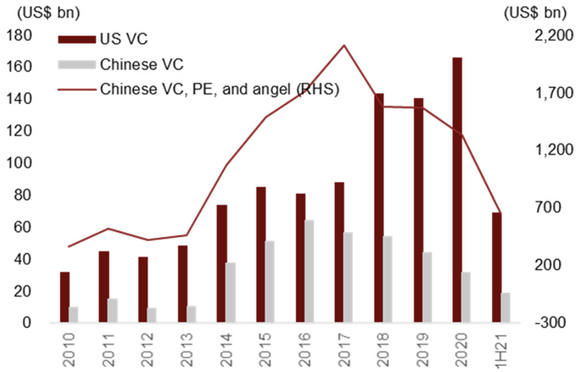

Fig. 7.14 Aggregate investment of Chinese VC firms has retreated. *Source* Pedata, NVCA, CICC Global Institute

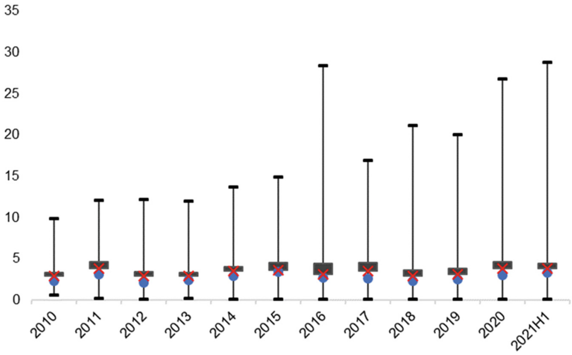

Fig. 7.15 Average time that Chinese VC firms hold an investment project. *Note* The upper and lower lines indicate maximum and minimum levels; the "x" in red indicates the average level; the blue circle reflects the median. *Source* Pedata, CICC Global Institute

they exit,[81] and IPOs account for more than one half of the total value (Fig. 7.16). This share has been rising in recent years. We believe Chinese VC firms rely more on IPOs for exit (Fig. 7.17). The experience from the US shows that VC firms with a focus on semiconductor, software, and pharmaceutical industries rely heavily on IPOs for exit.

As such, coordinated supports by primary and secondary stock markets help promote radical innovation. We believe the Japanese semiconductor industry's experiences and lessons echo our view. The bank-dominated innovation financing model played an important role when Japan attempted to catch up with advanced economies. It helped Japan become one of the most prominent players in the semiconductor sector. Efforts to catch up amid incremental innovation once threatened the US semiconductor industry. However, the US now enjoys clear advantages over Japan in semiconductor design and equipment, the two semiconductor segments with the highest gross margins and least likely to be replaced. We believe this underscores the positive impact of the capital market-dominated innovation funding model on radical innovation.

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[81] M&A is the largest exit channel for VC firms, in terms of the number of the projects that they exit.

Fig. 7.16 Share of each exit channel for VC firms in the US (in terms of value of exit projects). *Source* Pitchbook, CICC Global Institute

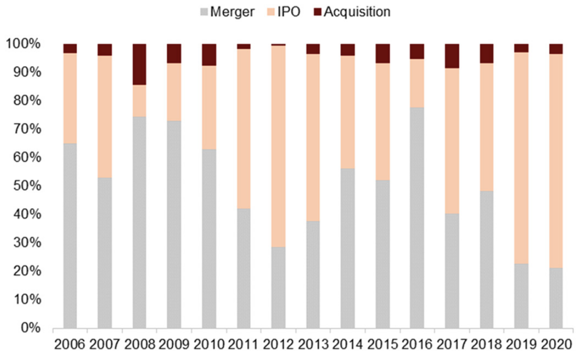
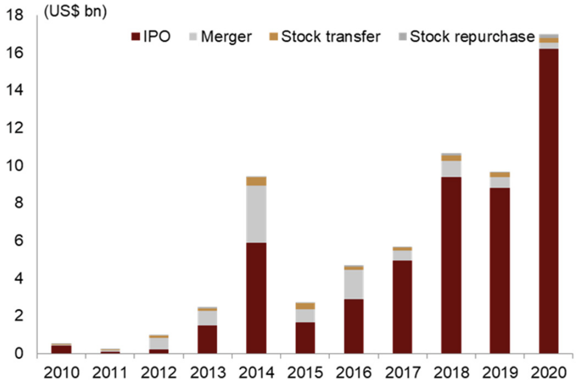


Fig. 7.17 Size of each exit channel for VC firms in China (in terms of value of exit projects). *Source* Pitchbook, CICC Global Institute



7.4.2.3 The Banking System: Potential Support for Innovation Should not Be Neglected

Before China issued new asset-management rules, Chinese banks invested their money in the private equity market through multi-tiered investment instruments.[82] Cooperating with trust firms was probably the most important channel, in our view, as reflected by the limited partnership (LP) structure of financial institutions that invest in private equity funds (Fig. 7.18). As banks invested in unlisted firms (and even multi-tiered higher-risk instruments), it would be inaccurate to say that banks cannot effectively support innovation due to their low-risk appetite, in our opinion.

In our view, the risk appetite of commercial banks is not closely related to corporate innovation, but rather it is mainly driven by their liabilities and operating models. Commercial banks do not effectively support innovation among smaller firms with little collateral or startups with unstable cash flows, in our view. However, they do not refuse to support innovation among larger companies with ample collateral or startups

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[82] Private equity funds received much less money from trust companies after the new rules were released in 2018.

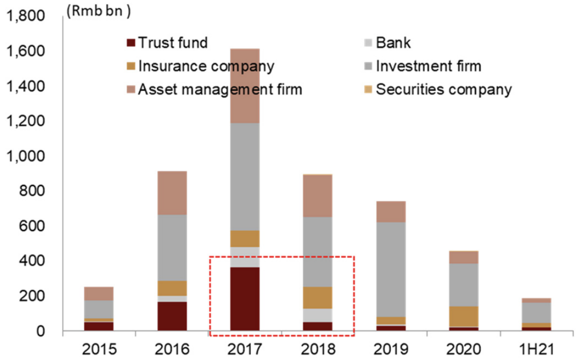

Fig. 7.18 The LP structure of financial institutions that invest in Chinese private equity funds. *Source* Pedata, CICC Global Institute

with stable cash flows. For instance, we note that bank credit played an important role in both China's ultra-high voltage (UHV) and high-speed railway (HSR) industries. Incremental innovation that can help a country catch up with its leading counterparts normally requires large quantities of resources. In our view, offering ample credit resources to large companies with strong innovation capabilities could be an ideal innovation-financing model to help lagging countries catch up with leading ones.

7.4.3 The Government's Role and Three Intervention Methods

The financial industry does not spontaneously invest in or promote innovation, regardless of whether the innovation funding model is "catching up" or "leading". When analyzing the government's role in innovation funding, we focus on two aspects (i.e., regulatory principles and policy stance) and three means of intervention (contributing capital directly, building a series of systems, and enhancing credit) (Fig. 7.19).

7.4.3.1 The Role of Regulatory Principle and Policy in Innovation Funding

We believe regulatory principle may have a bearing upon the impact of finance on innovation. For example, the subprime mortgage crisis in 2008 indicates that credit default swaps (CDS) are detrimental to financial stability, but innovation capabilities in the sectors that CDS covered improved substantially. The US banking system had a similar situation. After the US loosened banking regulation in states, a number of banks became more competitive than before, thereby hindering innovation. As a result, we believe that as existing banks in any given state faced new competitors, a detriment to financial stability, they subsequently became less influential, a benefit to promoting innovation.

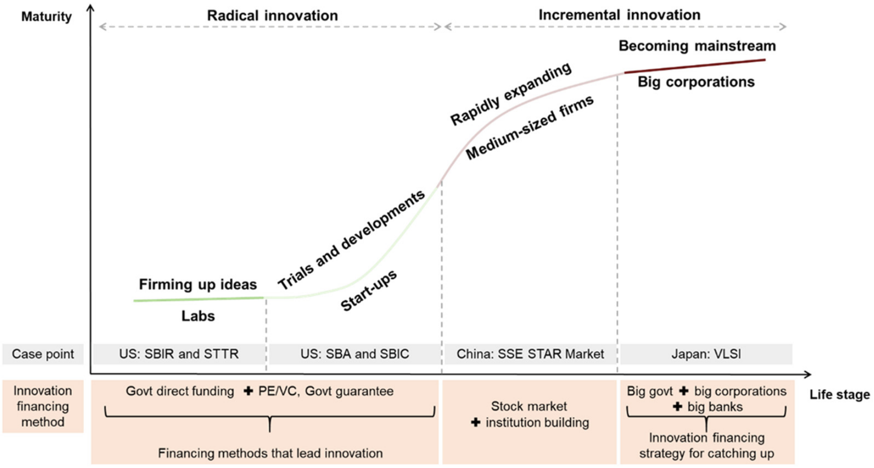

Fig. 7.19 The role of policies in innovation funding. *Source* CICC Global Institute

Overall, these two cases indicate that regulatory principle should ensure a balance between financial stability and innovation motivation instead of focusing too much on financial stability. As mentioned, financial structure is also important to the relationship between finance and innovation. Financial structure represents a system arrangement that relies heavily on a country's development models, and its formation is closely related with the policy stance that the government selects amid important historical events.

7.4.3.2 Three Methods of Policy Intervention in Innovation Financing

There are three main methods for the government to intervene in innovation financing. The first is direct investment, which overcomes the constraint of fiscal money shortage. Chinese firms or government agencies became a major source of financing for Chinese VC funds. This represents an important change in funding structure of Chinese VC funds during the past decade. Firms or institutions backed by governments contributed more than half of the total fundraising volume of Chinese VC funds. Government guiding funds mainly invested in angel funds and VC funds that were in the early stages of development. As these angel funds and VC funds are more important to innovation activities than their counterparts in other stages, the government's direct investment in them can effectively support innovation.

The second method is system building, which allows moderate valuation bubbles to internalize positive externalities of technological innovations. An important reason why capital markets and banks do not spontaneously invest in or promote innovation is that the financial benefits of innovation activities are not attractive enough. Settling this issue is an important part of the efforts to build a closed innovation loop, in our view, driven by both governments and companies (Figs. 7.20 and 7.21). On the one

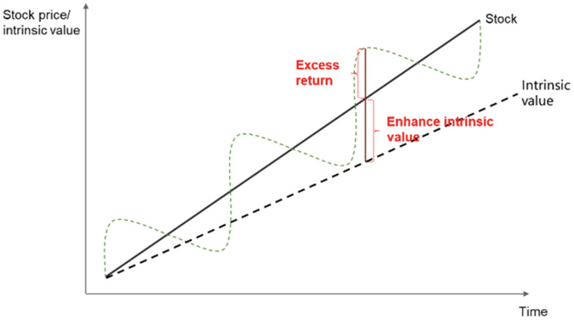

Fig. 7.20 Two options that can enhance innovation returns. *Source* CICC Global Institute

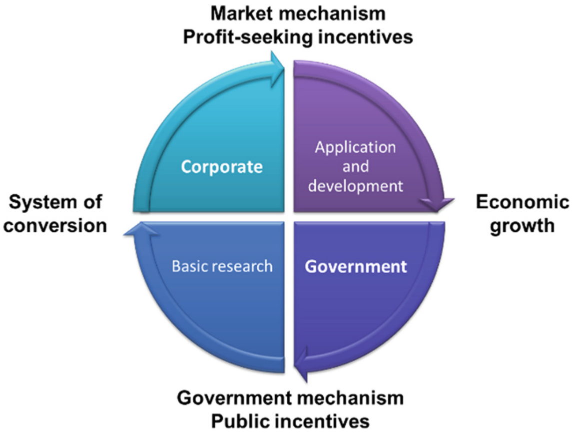

Fig. 7.21 The innovation loop driven by both governments and companies. *Source* CICC Global Institute

hand, from the perspective of cash flow discounting, we believe innovative firms need to enhance their intrinsic value, which requires extending their expected lifecycle and/ or improving cash flow expectations. On the other hand, in addition to formulating reasonable accounting systems, the role of monopoly in enhancing a company's intrinsic value should not be overlooked, in our view, as patents are essentially an artificially-created monopoly and help companies enhance their intrinsic value.

Enhancing companies' intrinsic value undoubtedly helps raise expected returns. However, if the stock market is a perfect and effective market, share prices would always equal per-share intrinsic value and discounted cash flow value would be the same as one-off revenue from stock sales. In other words, there would be no excess returns. In fact, the stock market is not a perfect and effective market. Given that Graham's analogy that the stock market is a "voting machine",[83] share prices being overvalued or undervalued is nothing new. When a stock has expensive valuations, investors can exit by selling the stock at a price higher than intrinsic value, thereby enhancing the returns on investment in technological innovation. In our view, creating

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[83] Graham, B., Dodd, D. (1934) Security Analysis.

a stock market that helps technological innovation investors exit could boost the likelihood of generating excess profit, internalize positive externalities of innovation activities, and have the capital market or banks more interested in supporting innovation. In addition, it also serves as an important mechanism to promote industrialization of R&D achievements.

The third method is credit enhancement. This method, together with direct fiscal backing, is an important way for the US government to push financial industry to support innovation. The typical options of direct fiscal funding include SBIR, STTR, and direct fiscal subsidies. However, credit enhancement is a more effective way in which the US government steers the financial industry to support innovation. Credit enhancement is widely seen in innovation projects that are funded by bank credit, capital markets or a combination of both.

First, the US government incentivizes banks to support innovation by providing credit enhancement supports to innovators. The US government has achieved this goal by establishing a state-owned federal financing bank and provide guarantees to private banks. As stated earlier, banks require borrowers to offer collateral and have ample cash flows due to their liability operation model. Although we believe it is inaccurate to say that banks cannot effectively support innovation, banks simply choose not to support innovation activities of startups or SMEs spontaneously. Therefore, offering guarantee services to startups and SMEs (e.g., credit guarantee programs, loan interest subsidies, and IP financing) is an important way through which countries push banks to issue loans to fund corporate innovation.

Second, the US government provides credit enhancement services to the capital markets' support for innovation activities. A typical example is the SBA's SBIC program. Initially, the SBA provided financing supports by directly purchasing the bonds issued by SBICs. After the US Congress passed the Public Law (2–213-DEC. 22) in 1971, SBA was authorized to provide guarantees for the bonds issued by SBICs. This credit enhancement practice became a mainstream way for SBA to support the SBICs' financing activities. As SBA's purchase of defaulted guaranteed loans is lower than the total amount of approved guaranteed loans (the purchase being less than 10% of the total amount over the past decade), its credit guarantee can attract much more money than direct bond purchases to support SBICs' innovation activities even if the government does not increase spending on SBIC programs.