Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development ·
Institute of Climate Change and Sustainable Development, Tsinghua University *Editors*

China's Resources, Energy and Sustainable Development: 2020

Springer

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Foreword I

Global climate change has become one of the gravest challenges that impede human survival and development in this century. Though global climate governance has moved into a phase characterized by full implementation of Paris Agreement, actions in the NDCs submitted so far are still not ambitious enough to keep global temperature increase below 2 °C. The IPCC's Special Report on Global Warming of 1.5 °C has underscored the urgency of tackling climate change, reinforcing and advancing the global target of "carbon neutrality". In the meantime, however, the world is witnessing an unprecedented change that is rarely seen in a century, which leads to greater uncertainty in the fight against climate change. More than ever, countries need to work together to advance climate governance and sustainable development.

China has always viewed addressing climate change as its major responsibility and a central part of promoting energy and economic transition, eco-civilization and a community with a shared future for mankind. Over the years, China has continued to implement and strengthen its national strategy on climate change, set targets and action plans for energy conservation and emission reduction in a bid to achieve a sustainable development of green, low carbon and circular, and demonstrate its leadership in the low-carbon transition of global energy and economy. As evidenced by China's policies and practices, there could be alignment and synergy between tackling climate change and driving sustainable development, because: (1) the fight against climate change will prompt the low-carbon transition of energy and economy, upgrade industrial structure and boost sustainable economic and social development; (2) active efforts to tackle climate change will contribute to co-governance of environmental protection and high-quality development, create a win-win scenario of high-quality growth, environment improvement and CO_2 emission reduction, and promote ecological civilization; (3) extensive engagement and active leadership in global climate governance will help build a community with a shared future for mankind. Increasing international cooperation in advanced energy technologies and industries not only boosts win-win cooperation and common development among countries, but also facilitates global response to ecological crisis, with more common interests and potential for cooperation, thus becoming the pioneer and paragon for building a community with a shared future for mankind.

China's Resources, Energy and Sustainable Development: 2020 represents the latest outcome of research organized and sponsored by Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development, and supported by Tsinghua Institute of Climate Change and Sustainable Development. The research centres on the theme of low-carbon transition in the context of global climate change and explores the topic of resources, energy and sustainable development which involves energy transition, pattern of urbanization, urban low-carbon actions, power system transition, water management, electric cars, and iron and steel industry among others, based on the practice of China in different fields. The book is expected to shed light, in a holistic manner, on the issues and interrelationships between resources, energy and sustainable development amid global climate change by adopting a multi-disciplinary perspective, and inform policies and management regarding climate change and sustainable development.

May 2020

Jiankun He
Chairman of Academic Committee of Institute of
Climate Change and Sustainable Development
Tsinghua University, Beijing, China

Foreword II

Climate change represents an unprecedented challenge for the world, but we believe that feasible pathways exist to develop a successful low-carbon economy. Companies, including ours, should be clear about how they plan to tackle climate change. As the world needs more materials and energy to prosper and provide people with a better quality of life, it also needs materials that have been produced in an economic and sustainable way, with fewer emissions and with respect to communities. We recognize both the challenge and opportunity in this and want to be part of the solution.

Climate risks and opportunities have formed part of our strategic thinking and investment decisions for over two decades. We now have a portfolio well positioned for the transition to a low-carbon economy, and we are the only major diversified company in the industry not involved in fossil fuel extraction. The materials we produce are essential to the low-carbon transition: aluminium used in electric vehicles, copper used to build wind turbines and iron ore used to create critical infrastructure.

Our goal is to play an active role in finding climate solutions, and we will do this through partnerships. Clearly, everyone needs to play a part: from customers to suppliers, from communities to governments, and from civil society organizations to business. Universities also have an essential role in finding and developing those solutions. This is why we are looking to collaborate with partners across the value chain.

The Tsinghua-Rio Tinto Join Research Centre demonstrates our commitment to developing a long-term strategic partnership with China. As China is attaching increasing importance to the quality of development in the New Era, the research projects conducted by the Tsinghua-Rio Tinto Centre will become even more relevant to China's long-term strategic goals.

Tsinghua University is one of China's most prestigious and influential universities and follows the spirit of "actions speak louder than words". Tsinghua is committed to developing innovative solutions that will help solve pressing problems in China and the world, by setting its sight on the frontiers of science and technology that align with the country's strategic objectives.

The announcement by President Xi Jinping that China aims to have CO_2 emissions peaks before 2030 and achieves carbon neutrality before 2060 is ambitious and encouraging. We expect China to strengthen its national strategy on climate change to achieve these goals and accelerate the low-carbon transition in power, industry and transport. We are delighted to be working with and supporting the development of Tsinghua University to share and implement research results, and most importantly, to make contributions to the sustainable and low-carbon development of China.

China's Resources, Energy and Sustainable Development: 2020 captures the latest thinking on critical issues on the low-carbon transition from the Tsinghua-Rio Tinto Joint Research Centre. The multidisciplinary approach brings new insight to address challenges of sustainable urbanization, low-carbon energy and transport, water resource management and the transition of the iron and steel industry.

I want to take this opportunity to express my sincere appreciation to Prof. Jiankun He, Prof. Li Zhen, Prof. Ma Linwei and other professors for their devotion and hardworking for the Tsinghua-Rio Tinto Joint Research Centre, and for their efforts and time for making this important book published.

October 2020

Simone Niven
Corporate Relations Group Executive
Rio Tinto, London, United Kingdom

Preface

As a big country in developing and utilizing resources and energy, China is also spearheading sustainable development. Massive development and utilization of resources and energy in the country have given rise to the huge sustainability challenge unseen in human history. To combat global climate change as its economy took off, China has made enormous efforts in driving sustainable development of resources and energy and low-carbon transition through building eco-civilization and a human community with a shared future. However, during the low-carbon transition, the serious challenges of resources, energy and sustainable development still require further research and response.

This book revolves around low-carbon transition with a focus on Chinese practice, seeking to explore the key challenges, solutions and policy recommendations of resources, energy and sustainable development from multiple lenses. Chapters 1, 2 and 3 lay out China's energy transition strategy, the interaction between rapid urbanization and low-carbon development as well as cities' transition towards low-carbon societies in the light of climate change and sustainability demand; Chapters 4 and 5 highlight power system and water resources, respectively, examining the joint low-carbon transition of power-grid-load, current management and challenges of water resources and its impact on low-carbon power transitions; Chapters 6 and 7 look at key metal minerals and bulk metal minerals, respectively, to illustrate the impact of the burgeoning electric vehicle market on the sustainability of key mineral resources and the technological options of low-carbon development in the steel industry.

In view of the complexity of resources, energy and sustainable development, Tsinghua University put together its research teams from its Low-carbon Energy Laboratory, Department of Energy and Power Engineering, Institute of Nuclear and New Energy Technology, School of Environment, Department of Electrical Engineering and School of Public Policy and Management, co-founded the Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development (hereinafter referred to as the Centre), together with Rio Tinto in 2012, and assembled an interdisciplinary research team to study resources, energy and sustainable development issues. In 2015, the Centre published a Chinese book entitled *Resources, Energy and Sustainable Development in China* (Beijing, Science Press), which focused on the hot issues of resources, fossil energy and new energy at that time. Afterwards, the Centre went further in incorporating research resources of Tsinghua University, including the Institute of Climate Change and Sustainable Development, the Department of Earth System Sciences, the School of Social Sciences and the School of Vehicles and Mobility, and organized interdisciplinary research that was more dedicated to the issue of low-carbon transition. Five years later, the Centre authored this English book based on the new research to showcase its recent findings for the reference and comments of international peers.

This book would not have been possible without the guidance from members of the academic committee of the Centre, including Jiankun He, Li Zheng, Yao Qiang, Wang Can, Zhang Xiliang and Wang Zanji and assistance from Ms. Simone Niven, Mr. Binyan Ren, Ms. Helena Robin Bordie, Mr. Sunny Song, as well as support from the faculty and students of Tsinghua University. Special appreciation goes to all of them.

Beijing, China
September 2020

Tsinghua-Rio Tinto Joint Research Centre for
Resources, Energy and Sustainable Development
(TRTC), Tsinghua University
The Institute of Climate Change and Sustainable
Development (ICCSD), Tsinghua University

Contents

Chapter 1
China's Energy Transition Strategy in the Context of Global Climate Change

Linwei Ma, Christine Yuan, and Honghua Yang

Abstract Worsening climate change has brought grave challenges to global energy development. All countries need to make urgent joint actions to speed up low-carbon transition of the energy sector. China, as the largest energy-related greenhouse gas emitter, plays a crucial part in global low-carbon energy transition. Clear strategic guidance is one of the indispensable factors for the country's successful transition. With the integration of energy system in mind, this chapter builds on the basic concepts of energy transition strategy and framework of system analysis to elaborate on China's energy transition strategy amid global climate change. The chapter contains three sections: energy challenges in China, the history, recent trends and future path of China's energy system, and policy recommendations for energy governance and energy markets. Overall, the challenge of China's energy transition in the context of global climate change lies not only in the call to expedite carbon emission reductions in the energy system, but also in the need to address other energy issues such as energy equity, energy security, and environmental protection. To solve all these issues, it must consider the unique evolution and changing pattern of China's energy system itself, follow the mechanism, and meticulously craft the strategy of energy transition (energy revolution) that suits the national situation. Under the policy objectives of the energy revolution, such as capping total energy consumption, peaking carbon emission, and increasing the share of non-fossil energy, China must accommodate energy system integration relative to coordination between energy and economy, between energy and infrastructure and between energy and regional development. To this end, this chapter envisions the "3+1" energy system integration, and proposes to build a regional smart energy system that features the blend of "smart energy farms—smart energy towns—smart energy industrial parks—smart energy transportation networks". However, this poses new challenges to the existing energy governance system and energy market management. Therefore, it's essential

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for China to empower energy planners, spur bottom-up energy innovation, remove the barriers to cooperation between the energy industry and enterprises, and redouble efforts to strengthen the energy management information system and dedicated think tanks in the energy sector.

Keywords Climate change · China’s energy system · Energy challenges · Recent trends · Future path · “3+1” energy system integration

1.1 Basic Concepts and Analysis Framework of Energy Transition Strategy

Energy transition refers to the paradigm shift in the energy system over time as required by the sustainable development goals. The increasingly severe global climate change has called for more efficiency in energy transition than ever. Driving this process not only involves a higher uptake of energy-saving technologies and renewable energy, but also other spheres such as economy, society, and politics, hence a need to engage the whole society (Singh et al. 2019). In this circumstance, clear strategic guidance is critical.

For this purpose, this paper proposes the basic concepts of energy transition strategy and the system analysis framework to examine China’s energy transition strategy. As per the notion of “sustainability-energy system-social governance-market operation” (Ma et al. 2018) coined by the author to study the strategy of regional energy development, energy transition strategy can be perceived as: “a master plan driving the overall revolution of the energy physical system of a specific social organization (global or regional) in order to meet the energy challenges of sustainable development”. The corresponding framework of system analysis is shown in Fig. 1.1.

In this analytical framework, the energy challenge of sustainable development is the background and constraints of the energy transition strategy; the strategy is mainly set by the energy governance system for the energy market system to consciously observe the principle of sustainable development and enable the transition of the energy physical system; the energy market system performs actual operations on the energy physical system, so that the resources input, energy output and emissions of the energy physical system can move towards the strategic goals of the energy system transition and sustainable development.

This chapter would revolve around this framework of system analysis and discuss China’s energy challenge, energy system, energy governance and energy market.

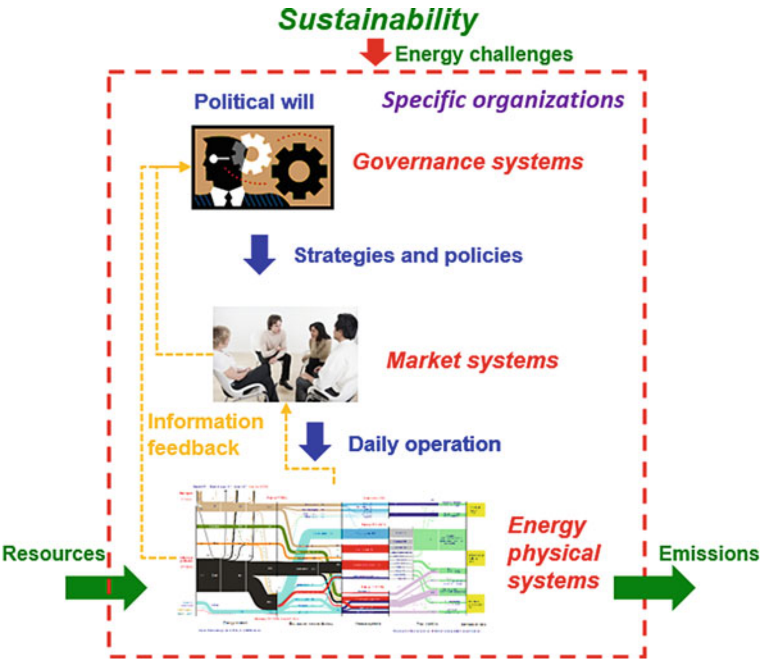

Fig. 1.1 Analysis framework of energy transition strategy

1.2 China’s Energy Challenge in View of Global Climate Change

1.2.1 The Global Climate Change Faces Severe Challenge

To tackle global climate change challenge, the Intergovernmental Panel on Climate Change (IPCC) issued a total of five scientific assessment reports between 1990 and 2014, underscoring the scientificity, urgency, and severity of the issue. The IPCC’s fifth report (IPCC 2014a, b) suggested that global warming was beyond all doubt, and that more than half of the observed increase of global average temperature from 1951 to 2010 was “very likely” (over 95% probability) caused by human influence on the climate. Unabated greenhouse gas (GHG) emissions will trigger a warming trend and long-term changes in all components of the climate system, increasing the likelihood of serious, universal and irreversible impacts on humans and ecosystems. Without greater mitigation efforts (reduction of GHG emissions), even with adaptation measures, the severe impacts and high risks of climate change will continue at least by the end of this century.

To deal with global climate change, the Paris Agreement was adopted at the UN Conference on Climate Change in 2015, which set the goal of “keeping global average temperature rise within 2 °C in this century” (UNFCCC 2015). However, the continued increase in global GHG emissions further enlarges the gap between the target. "Emissions Gap Report" (UNEP 2019) issued by the United Nations Environment Programme (UNEP) in 2019 found that the median global GHG emissions will be about 41 billion tons of CO_2 equivalent per year by 2030 if we want to achieve the 2 °C goal. Meanwhile, the National Independent Contribution (NDC) targets currently submitted by countries in the Paris Agreement indicated that by 2030, the amount of emissions could only be kept between 54–56 billion tons of CO_2 equivalent per year. Given the gravity of the issue, all countries must further accelerate the low-carbon transition to meaningfully reverse climate change.

The energy sector contributes more GHG emissions compared to others, mainly through CO_2 emissions during the combustion of fossil fuels. According to the fifth report of the IPCC (IPCC 2014a, b), if measured in terms of direct emissions, the sector of energy supply (mainly electric heating production) contributed the most, about 35% to global GHG emissions in 2010. It also made up 47% of the annual global anthropogenic GHG emissions from 2000 to 2010. If indirect emissions are taken into account, CO_2 emissions from fossil fuel combustion and industrial processes accounted for 65% of global GHG emissions in 2010 and 78% of global growth in GHG emissions from 1970 to 2020. To mitigate the effects of climate change, the energy sector, as the main source of greenhouse gas emissions, must drive low-carbon transition and create a new system based on non-fossil energy.

1.2.2 The World Faces Multiple Energy Challenges

Climate change has become a serious challenge for the sustainable development of global energy. Yet sustainable energy development entails multiple objectives. Other energy challenges, alongside climate change, include energy equity and energy security, etc. (IIASA 2012), which are also closely linked to human survival and development. Together with climate change, these challenges constitute "energy dilemmas" for the sustainability of global energy, due to certain trade-offs between other energy challenges and climate change. To illustrate, to rapidly enhance energy equity, energy demand will surge, leading to more potential fossil energy consumption; to ensure energy security, countries tend to prioritize the use of their own rich resources, such as shale gas in the United States and "coal to oil" in China, thus impeding the scale-up of non-fossil energy. To solve the dilemmas, complex and intertwined links between public and private institutions, government and regulatory agencies, economic and social factors, national resources, environmental issues, and consumer behavior should be built, which is not an easy task. The assessment report published by the World Energy Council (WEC) argues that most countries have failed to effectively address the "energy dilemmas", and there is still a long way to go for the meaningful sustainable development (WEC 2019). Examples for the substance and severity of the challenges could be found in energy equity and energy security listed below:

- **Energy equity**: Energy equity performs the basic mission of energy development by providing affordable modern energy services for all. At present, the world is still haunted by this challenge. For example, in 2016, 13% of the world's population lack electricity and 41% of the population were still using unclean cooking fuels and technologies; only 55% of renewable energy was of modern utilization with the rest coming from traditional biomass fuels such as fuelwood and charcoal. (UN 2018).
- **Energy security**: Currently energy security is not only about oil security, but also about power, natural gas and even end-use energy service security (Wang and Zhou 2017). Influenced by infrastructure and geopolitical factors, global energy security is still not optimistic. Major historic energy security accidents, including multiple oil crises, the power outage in the United States and Canada in 2003 (Zhou 2013), and the three gas disputes between Russia and Ukraine between 2006 and 2014 (Zhou 2014), have highlighted the importance and risks of energy security.

Apart from energy equity and security, other challenges also stand out in many countries, including regional environmental pollution from energy development and utilization, and how to support economic growth through the energy sector, etc.

1.2.3 Severe Energy Challenges in China

The multiple energy challenges in the world are complex in various countries. For China, the magnitude and scale of the problems are unprecedented in human history. The five energy challenges laid out by some scholars (Ni et al. 2008) early on continue to exist, or have even increased, including: (1) huge and dynamically growing energy demand. In 2017, China's primary energy consumption contributed 23.2% to the world's total consumption, averaging an annual increase of 3.9% over the past decade (BP 2019); (2) the rapidly rising dependence on imported oil and gas. From 2007 to 2017, China's foreign dependence on oil rose from 50.7 to 68.5%, and its dependence on natural gas surged from 1.8 to 37.9% (NBSC 2018); (3) severe conventional environmental pollution lingers, including air, water, soil pollution, etc. (Li 2018); (4) lack of clean energy services in rural areas and small towns with acute energy poverty, plus the massive use of inferior bulk coal, serious pollution of coal-burning, backward energy infrastructure, and inadequate use of renewable energy (Ni et al. 2019); (5) enormous and ballooning greenhouse gas emissions. In 2017, China's energy-related carbon emissions accounted for 27.6% of the world's total emission, with a 10-year average annual growth of 3.2% (BP 2019).

In the meantime, as global climate change accelerates and China's economic and social development enters a new phase, the dimensions of China's energy challenge have also undergone notable shift. For instance, the overcapacity at the energy supply side in the new era calls for speedier transition from fossil-based (particularly coal) primary energy utilization to a pattern driven by non-fossil fuels, while meeting the needs of high quality growth and supply-side reform; a need for transition from mainly centralized energy supply to moderately-sized distributed energy supply; a need for transition from an extensive mode of energy consumption featuring industrial use, especially that of energy intensive industries to a high-quality mode with residential and service usage as the mainstay. These critical issues merit high attention and good solutions during the low-carbon energy transition. The key lies in the collaboration of multiple energy sources and the smooth switch from the old to the new production capacity, which puts higher demand on the level and workload of energy system integration.

In addition to the aforementioned challenges, bigger challenges for China to accelerate the low-carbon transition comes from the "path lock-in" effect caused by the huge energy in-use stocks. For example: (1) Technology and economic lock-in. There is tremendous inertia for the type of energy economy relying on coal and other high energy-intensive sectors. The scale economy of traditional energy technologies and the long-term learning-by-doing development model make for their low cost and high performance, in contrast to new energy technologies that are unable to compete in the short-term (Klitkou et al. 2015). This undermines the motivation of enterprises to pursue low-carbon transition; (2) Social and cognitive lock-in. Stereotypes and living habits make people "selectively blind" to topics such as climate change that seem to bear little impact on their daily life (Nelson 2018). Moreover, user practices and lifestyle have been built upon traditional energy technologies and conventional way of supply and consumption. Triggering a switch would imply a change in the way of living, which faces problems of public acceptance and user participation.

1.2.4 Summary

The battle against global climate change calls for stronger efforts in low-carbon transition of energy systems in all countries. But the transition is facing multiple "energy dilemmas" including other energy challenges such as energy equity and energy security. China, in particular, is constrained by multifaceted and intertwined energy challenges: (1) vast and rising energy demand, with acute energy security and energy equity issue, heavy conventional environmental pollution from energy use and huge and surging greenhouse gas emissions; (2) the necessity to enable multi-energy synergism and smooth switch between old and new production capacity in the entire value chain of energy production and utilization, putting forward higher requirements for integrating energy systems; (3) the difficult elimination of the "path lock-in" effect from the huge social stocks of coal and high energy-intensive industries. To conclude, China is in an urgent need of exploring a path towards sustainable low-carbon transition based on the reality of its unique energy system.

1.3 The Past, Present and Future of China's Energy System

This section begins with a review of the history of China's energy system and its recent development, with a breakdown of historical stages. Secondly, the Sankey diagram tool was adopted to draw a full picture of China's energy flow, followed by analysis of the structural changes of the energy system from 2005 to 2015. Finally, the section explores the future direction for China's energy development, proposing a new concept named as "3+1" for energy system integration.

1.3.1 The History of China's Energy System

Based on the historical data of BP (BP 2019), the changes in China's primary energy consumption and its structure from 1965 to 2018 can be shown in Figs. 1.2 and 1.3. From 1965 to 2018, China's primary energy use increased from 131.47 to 3273.47 Mtoe, growing at 6.25% a year on average; meanwhile, energy-related CO_2 emissions increased from 488.53 to 9428.71 Mt, growing at 5.74% per year; coal had predominated the energy mix during the entire period, yet with decline from 87.0 to 58.3%.

Based on major typical periods and marked changes in the growth of energy consumption and primary energy mix, four stages of energy development can be discerned from 1965 onwards:

(1) 1965–1978, the first stage with the gradual economic recovery. China's energy consumption experienced a shake-up, hovering at a low range, and then climbing fairly rapidly. This period was characterized by the spike in domestic crude oil

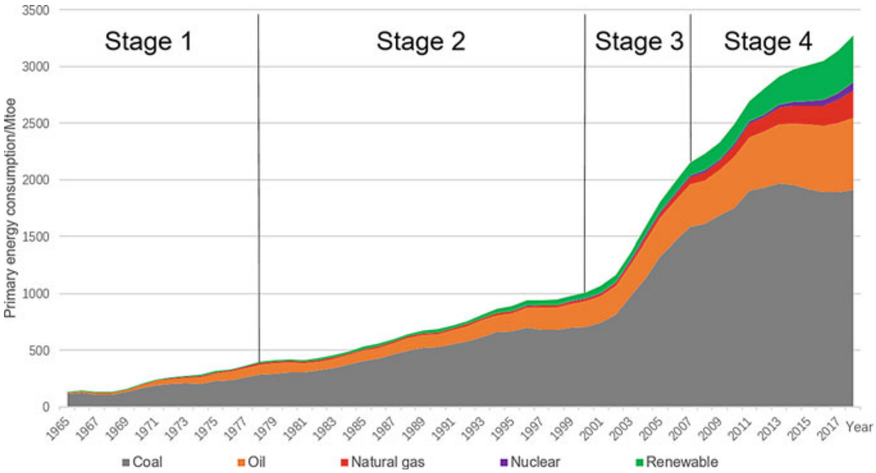

Fig. 1.2 Historical curve of primary energy consumption in China

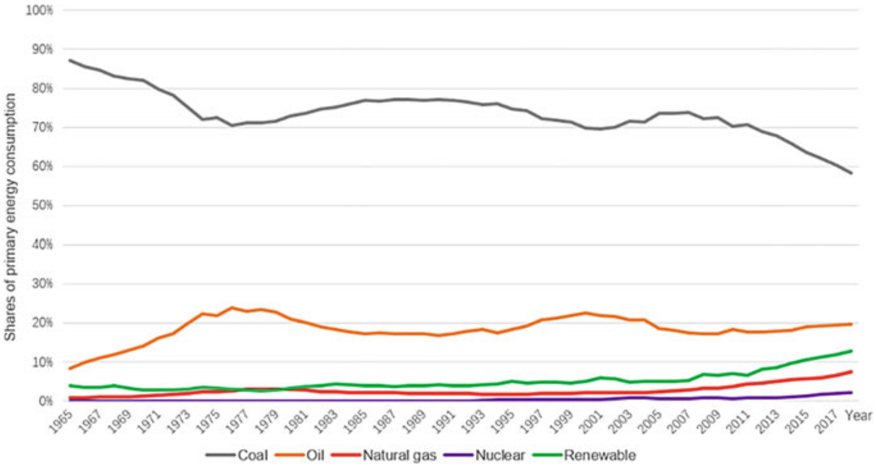

Fig. 1.3 Historical curve of primary energy consumption mix in China

production from 11.10 to 92.57 Mtoe, with an average annual growth of 17.72%, pushing up the share of oil in the energy mix from 8.4 to 23.3%, while the ratio of coal dropped from 87.0 to 71.2%.

(2) 1978–2000 was the second stage with smooth growth in energy use, which saw an increase from 397.07 to 1010.93 Mtoe, growing at only 4.34% annually on average, and the energy structure remained basically unchanged. The smooth growth was mainly attributed to China's reform and opening up in 1978 and the full recovery of light industry.

(3) 2000–2007, the third stage, witnessed sharp increase in energy consumption. China's joined WTO in 2001, and the subsequent opening of the international market to the country led to a surge of investment in energy-intensive sectors, driving up energy consumption from 1010.93 to 2149.64 Mtoe in just seven years, which hit an average annual increase of 11.38%. Energy-related CO_2 emissions from the sector also rose from 3362.70 to 7240.33 Mt, growing at 11.58% per year on average. In 2005, China overtook the United States to become the world's largest energy-related CO_2 emitter.

(4) 2007–2018 was the fourth stage when energy transition was progressed. As the extensive development of energy and economic had brought many problems in energy security and ecological environment, China made a hard yet resolute decision to transform the industry. For one thing, energy consumption continued to show an upward trend in order to support the burgeoning economy and society, making China surpass the United States as the world's largest primary energy consumer for the first time in 2009. On another hand, remarkable progress was made in energy transition during this period. Thanks to the control on total energy consumption, the average annual growth of energy consumption nosedived to 3.89%. The use of renewable energy jumped from 113.30 to

415.59 Mtoe, with an average annual growth rate 12.54%. The share of non-fossil energy grew from 5.9 to 13.9% while coal dropped from 73.7 to 58.3%. The coal consumption realized negative growth in 2014, and energy-related CO_2 emissions also fell for the first time in the same year.

Based on the foregoing, the 2005–2015 period was chosen for research. This decade was featured by a difficult energy transition, which was largely enabled by the government's strategic guidance. China's first comprehensive five-year energy development plan—the 11th Five-Year Plan for Energy Development (NDRC 2007a) was unveiled during 2005–2010, followed by the 12th Five-Year Plan for Energy Development (State Council 2013), the Renewable Energy Law of the People's Republic of China (National Energy Administration 2006), the medium and long-term development plan for renewable energy (NDRC 2007b), the 11th Five-Year Plan for Renewable Energy Development (NDRC 2008), and the "Strengthening Actions to Address Climate Change—China's National Independent Contribution" (State Council 2015) formulated in the new era to support the Paris Agreement. Identifying the trends of China's energy system during this period not only helps us understand the actual impact of previous policies on energy transition, but also provides reference for future strategies in this regard.

1.3.2 *Recent Trend of China's Energy System*

To understand the structural changes in China's energy system from 2005 to 2015, the 2005 China Energy Allocation Sankey diagram (Fig. 1.4) drawn by Ma et al (2012) was compared with the 2015 diagram (Fig. 1.5) by Yang et al. (2019). The diagrams reveal in details the flow and distribution of energy in various stages of the Chinese energy system, from sources, end-use conversion devices, passive systems

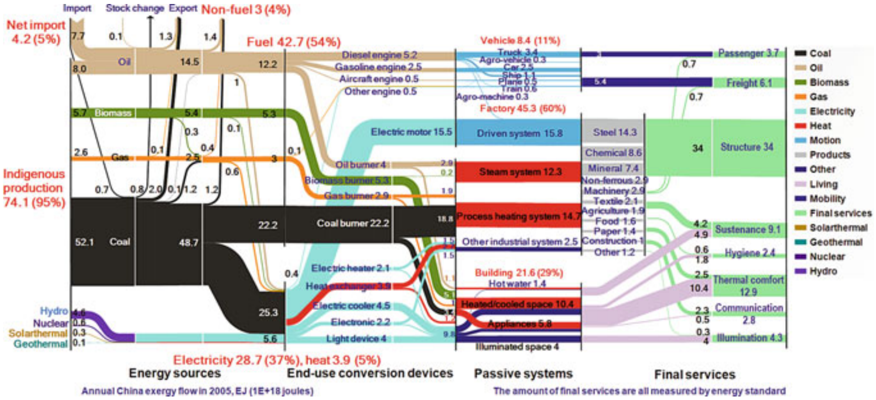

Fig. 1.4 China's energy allocation sankey diagram in 2005

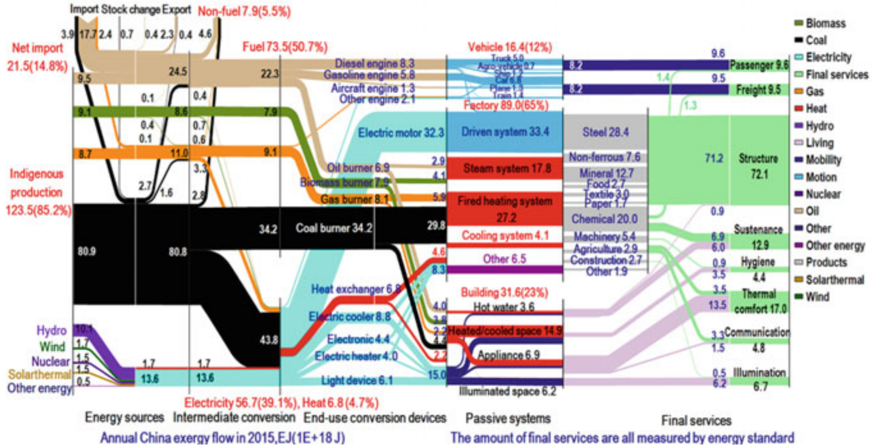

Fig. 1.5 China's energy allocation sankey diagram in 2015

to final services. In the diagrams, energy flows from left to right, with the thickness of the flow representing the size of energy, and colors showing different energy types and way of utilization. Since the two were drawn in the same format, a comparative analysis of each stage of the two diagrams would provide systematic and in-depth understanding of the recent trends of China's energy development.

1.3.2.1 Energy Supply

Coal Remains the Most Important Primary Energy, yet Its Proportion Saw a Significant Decrease.

A comparison of the two Sankey diagrams found that coal was still the main primary energy in 2015, accounting for more than 60% of the total primary energy supply. However, the biggest change in the structure of energy supply in that decade decreased significantly by 6.4% of the proportion of coal. This is precisely what Chinese government had accomplished in accelerating clean and low-carbon transition of the energy system when the country was challenged by the worsening environment and climate change. Over the ten years, China's 11th Five-Year Plan for Energy Development and the 12th Five-Year Plan (NDRC 2013) both prompted the reduction of coal consumption by formulating clear binding goals, such as a 20% reduction in energy intensity and a 17% reduction in CO_2 emission intensity, etc. With strong political will and consistent policy guidance, the plans had resulted in notable outcome.

Natural Gas and Renewable Energy Become Important Supplement

The decreased share of coal was largely due to the substantial increase in natural gas, hydropower and wind. The proportion of natural gas in China's primary energy grew from 3.2 to 7.5%, whose proportion had the largest increase among all primary energy sources. This was attributed to China's vast gas pipelines built during the "11th and 12th Five-Year Plan periods". The relative growth rate of hydropower reached 120%, and its proportion increased by 0.2%. Wind power capacity expanded by as much as 55 times, and its share rose by 1.1%. During the "12th Five-Year Plan" period, wind power was viewed as the second most important priority of renewable energy development.

Increasing Dependence on Foreign Oil and Gas Undercut Energy Security

The spike in oil and gas consumption had threatened energy security. Although China had made a lot of efforts in domestic oil and gas development, it was still difficult to keep up with the rapid growth of oil and gas demand, which made oil and gas consumption mainly rely on imports. By 2017, foreign dependence of oil had approached 70%, and gas nearly 40% (NBSC 2018). This had posed challenge to China's energy security. Meanwhile, the rapid penetration of renewable energy such as solar and wind had brought about serious wind and solar curtailment.

1.3.2.2 Industry

With Rapid Growth of Industrial Energy Consumption and Predominant Steel Industry, It is in Urgent Need to De-capacity.

Industrial passive systems remained the largest energy consumer in terms of end-use. The total industrial energy consumption has maintained sustained growth, with its proportion up from 60% in 2005 to 65% in 2015. The ferrous metal mining and manufacturing, predominant steel industry, contributed the biggest growth, mainly because China was still in the process of industrialization which entailed increasing steel consumption on a per capita basis. In 2008, China offered RMB 4 trillion stimulus package to boost infrastructure construction. Due to excessive expectation of demand increase, plenty of steel production plants were launched and subsequently laid idle, leading to glaring overcapacity in 2015 with great inertia. Thus, achieving de-capacity in the steel sector was a matter of great urgency in facilitating low-carbon transition.

Chemical and Non-ferrous Industries Should Be New Focus of Energy Saving and Emission Reduction in Future

Chemical product manufacturing was the second largest energy consumer, only after steel production, and was the one with the biggest increase in the proportion of energy use among industrial passive systems (up 3.5%). Despite the energy consumption was relatively small, the non-ferrous metal industry created high growth in embodied carbon emissions due to the large amount of electricity use in its production process, and the share was up by 2.9% (carbon emission data is calculated based on energy flow data and IPCC carbon emission factors, the same below). This was because macroeconomic development, growing urbanization and industrial transition provided a fertile ground for chemical and non-ferrous metal sectors. Financial data of industrial enterprises of the National Bureau of Statistics (National Bureau of Statistics 2016) showed that in 2015, despite a fall in total profits of large industrial enterprises, chemical raw materials and chemical products manufacturing saw their profits increase by 7.7%, the biggest growth among all industrial sectors. The considerable profit from the increased demand had brought huge opportunities for chemical companies.

1.3.3 The Growth of Energy Consumption for Non-metallic Mining Slowed Significantly

On the contrary, the growth of energy use for non-metallic mining dramatically slowed down, with its proportion down 2.1%, the fastest decline among all industrial sectors. This was attributed to the fact that China strengthened rectification of non-metallic mines during the 12th Five-Year Plan period, regulating the mining market, and shutting down nearly 10,000 non-compliant enterprises (Ministry of Natural Resources 2016).

1.3.3.1 Transportation

Road Passenger Transportation Surpassed Road Freight as the Major Transport Energy Consumer

Road passenger transportation and freight transportation remained important energy users in the vehicle passive system, but the ratio of these two had undergone a reversal. The share of energy use by road freight was down from 40.5 to 30.5%, while that of road passenger transport rose from 29.8 to 41.5% and overtook freight to become the biggest energy consumer in transportation. This reversal was partly due to China's constantly improving road traffic network. During the "12th Five-Year Plan" period, national highways had reached 99.9% of townships (towns), the length of expressways totaled 123,500 km, and a nationwide expressway network had taken shape (Ministry of Transportation 2017). It was also related the change in people's consumption pattern and life style, as could be seen in the popular ownership of private cars. The number of private cars in 2015 was over ten times that of 2005 (Wang 2016). This trend had pushed up oil imports, which posed increasing threat to energy security. Meanwhile, it had led to substantial increase in pollutants and CO_2 emissions (the proportion of carbon emissions rose by 9.5%), worsening urban air pollution, thus becoming a major contributor to carbon emissions.

The Growth in CO_2 Emissions from Road Freight and Shipping Slowed Down

The growth of energy use from trucks and ships slowed down, with growth rate less than 50% (other transportation modes witnessed over 100% increase in energy consumption), and there was no significant rise in carbon emissions. This was closely associated with economic transition. In 2015, the tertiary industry as a percentage of GDP exceeded 50% for the first time. As the tertiary industry required less physical goods than the other two during that period, the overall demand for freight transport and shipping cooled down.

1.3.3.2 Building

The Proportion of Energy Consumption in Building Fell, Among Which the Energy Consumption of Space Cooling/Heating and Hot Water Systems Increased Significantly

The share of energy consumption from building dropped by 6.0% over a decade, which was a stark contrast to the industrial sector. This was largely due to improved building energy efficiency. In the building passive system, space cooling/heating saw the greatest increase in energy consumption, and occupation ratio of the hot water system showed the highest increase (up by 4.9%). This change was mainly driven by rising living standards of residents, pursuit for quality of life, the need for personal hygiene, and the continuous upgrading of regional hot water supply.

Appliances Saw Lower Proportion in Energy Consumption, but with Surging CO_2 Emissions

Despite only 19% growth rate in energy use, home appliances reported 158% growth rate in CO_2 emissions, with a spike in carbon emissions per unit of energy consumption. This was mainly because during the replacement of traditional home appliances, most of the traditional biomass-based devices ceased to exist (e.g.: wood fire stoves replaced by rice cookers, gas stoves, etc.), while biomass was considered carbon neutral. This accounted for the dramatic rise in carbon emissions despite small changes in total energy use.

1.3.3.3 Final Service

Demand for Structural Material was the Biggest Driver for Energy Consumption and CO_2 Emissions

At the final service of energy, the structural service was always the most important energy service, making up over half of the total, and rising rapidly. In 2015, it registered a 7.5% growth compared to 2005, resulting in increase in CO_2 emissions as a whopping 2218 Mt. This was, in large part, fueled by China's massive urbanization in the past decade and the booming infrastructure development. From 2006 to 2011, the total output of the construction industry had been growing at over 20% for six consecutive years (Ministry of Housing and Urban-Rural Development 2017), a pillar industry for economic growth.

Energy Demand for Thermal Comfort Service and Sustenance Service Slowed Down

Thermal comfort services and sustenance services were marked by the reduction in energy consumption and carbon emissions as the final service, which had been primarily the result of urban central heating pipeline networks, replacement of traditional heating methods, more energy-efficient home appliances and a much smaller primary industry as a percentage of GDP. This also reflected the shift of people's pursuit from trying to make their basic livelihood to aiming for a quality life.

1.3.3.4 Summary

China's energy is undergoing transition from high-speed to high-quality growth. Two major trends can be found in the recent development:

1. China is still undergoing rapid industrialization and urbanization. Spectacular infrastructure construction and fixed asset investment have been accompanied by huge and continuously rising demand for structural materials, creating a mushrooming industrial sector (steel and chemical industry in particular) that is often troubled by overcapacity. The high dependence of such industries on coal and electricity presented enormous challenge for China to decoalize and decarbonize its energy system in the short term.
2. People's rising demand for high-quality life has changed the structure of energy end use. For instance, the increased need for passenger transportation, hygiene and communication services has resulted in a marked increase in the energy consumption of hot water supply in passenger cars, aircraft, buildings, and of modern appliances, making them the new driver of carbon emissions.

Therefore, striking balances between economic development and people's needs for a better life and the clean, low-carbon, safe, and efficient goals is crucial for China to achieve the integration and low-carbon transition of its energy system.

1.3.4 Future Path for China's Energy System

Considering the serious energy challenge, if the current development of China's energy system continues, double challenges would emerge: for one, an inefficient industry burdened by overcapacity with great inertia; for another, a tension between heightened environmental and climate constraints and increasing demand for high-quality energy services. China already has come up with the overall plans and goals for energy transition. However, a deep reflection on the coordinated development of energy and other fields in terms of system integration is required to link the relatively independent goals and requirements under the existing policies to achieve the synergy of all to meet climatic conditions. This section centers on the "three coordinations" of energy and economy, energy and infrastructure, and energy and regions, and to this end, offered a new approach of energy system integration featuring "smart energy farms—smart energy towns—smart industrial parks", paving the way for low-carbon energy transition.

1.3.4.1 Overall Plans and Goals for China's Energy Revolution

To spur energy transition, China has put in place a relatively clear strategic framework. In China, the term "energy transition" largely equate with "energy revolution". Or rather, "energy revolution" represents the Chinese version of "energy transition". The term "revolution" also signifies the urgency and determination of China's energy transition and its resolve to make it a reality.

The Chinese government has unveiled the overall policy requirements of the energy revolution. The report of the 18th National Congress of the Communist Party of China in 2012 (Hu 2012) first proposed the concept of the energy revolution, requesting "to boost energy production and consumption revolution, cap total energy use, strengthen energy conservation and consumption reduction, support energy-saving low-carbon industries and new energy, renewable energy development to ensure national energy security." Subsequently, General Secretary Xi Jinping further illustrated the dimensions of energy revolution characterized by "four revolutions, one cooperation" in 2014 (Xi 2014), namely: (1) advance the energy consumption revolution and curtail unreasonable energy use; (2) promote energy supply revolution by creating a diversified supply system; (3) facilitate energy technology revolution to upgrade industries; (4) drive energy system revolution to fast-track energy development; (5) step up all-round international cooperation to enhance energy security in an open manner. The report to the 19th National Congress of the Party in 2017 (Xi 2017) also indicated the need to "press ahead with revolution in energy production and consumption, and build a clean, low-carbon, safe and efficient energy system." These dimensions and goals of energy revolution had been widely deployed in China, such as in the 13th Five-Year Plan for Energy Development (NDRC 2016b).

It can be seen that the focus of China's energy revolution has expanded from energy conservation, usage reduction and energy security to consumption, supply, technology, institutions and international cooperation. In recent years, "clean and low-carbon" became the key focus. This means that in the context of global climate change, low carbon is increasingly becoming one of the key goals of China's energy revolution. With this in mind, the "Energy Production and Consumption Revolution Strategy (2016–2030)" (NDRC 2016a) went further in setting out two milesones: (1) By 2030, the total energy consumption should be capped below 6 billion tons of standard coal; non-fossil energy and natural gas should account for about 20% and 15% respectively; carbon emissions should peak and should do so as soon as possible; (2) By 2050, total energy consumption would stabalize, with over 50% from non-fossil energy.

Despite the aforementioned strategic masterplan and goals of the energy revolution, the task of energy transition involves multi-faceted, multi-layered and intricate interactions between multiple forms of energy and technologies, which goes far beyond the scope of the current policy. To illustrate, though the guideline of "four revolutions and one cooperation" points direction for energy consumption, energy supply, energy technology, energy system and international cooperation, this approach may give rise to separate management of these interconnected workstreams. Therefore, it's essential to contemplate the means to build linkages between the overarching energy revolution strategy and objectives and the micro-level energy system engineering and technical work. And this would warrant enhanced academic research and policy formulation on energy system integration at the mesoscopic level to match the macro and micro elements.

Aside from the existing goals, the increasing risk of climate change might call for tightening these goals to accommodate new climate requirements. For example, the IPCC's Special Report on Global Warming of 1.5 °C (IPCC 2018) has imposed more stringent emission reduction requirements on countries to keep temperature rise within 1.5 °C. This means that China needs to continue strengthening energy system integration under the existing policies to attain the set goals, and at the same time envision a more forward-looking approach to create an energy system with higher efficiency and greater uptake of non-fossile energy in order to embrace climate goals.

The following is based on our academic research on energy system integration, and explores the coordinated development of China's energy transition and other important areas. The "three coordinations", i.e.: coordination between energy and economy, between energy and infrastructur, and between energy and regions, was examined in detail, together with an illustration of the new solution of energy system integration, i.e. "smart energy farms—smart energy towns—smart industrial parks—smart energy transportation networks" that accommodate the "three coordination" requirements and even harsher emission reduction goals.

1.3.4.2 "3+1"Energy System Integration

Energy system integration is an overall strategy that puts together multiple energy sources, technologies, and systems, which involves design, integration, optimization, scheduling, and infrastructure construction and operation of the overall energy system. It aims to synergize various energy sources and sectors through maximizing their complementary strength, thereby achieving the optimization of the overall energy system.

A bridge connecting macro-policy requirements and micro-technical work, energy system integration seeks to address two issues: (1) link energy system integration with macroeconomic and social sustainable development; (2) apply energy system integration to the implementation of specific fields and technologies. As President Xi Jinping pointed out: "Innovation represents a systematic project. The chains of innovation, industry, capital and policy are intertwined and mutually supportive. Carrying out reform in just one or a few processes are far from adequate. It must be done in a holistic approach and advanced with unwavering commitment. Technological innovation should go hand in hand with institutional innovation. We must get "both wheels" in motion (Xi 2016)". Energy system integration can be perceived as a key component linking the "two wheels" in the energy sector.

Based on the previous research conducted by the author of the chapter on energy system integration, the key of energy system integration in China's energy low-carbon transition involves at least three major issues: energy and economic coordination, energy and infrastructure coordination, and energy and regional coordination. Each of the three coordinations is discussed below, and building on the discussions, a new approach of energy system integration that reinforces the three coordinations is laid out. The three coordinations and one approach are generally referred to as the "3+1" approach for energy system integration.

Energy and Economic Coordination—Prioritize and Formulate Sound Plans for Coordinating Energy Supply and Demand

China has experienced a great amount of problems of mismatch between energy and economic development in the past, which is mainly manifested in the frequent disconnection between energy supply and demand during economic development, resulting in either shortages or surplus of energy provision and subsequent huge energy waste, as shown in Fig. 1.6 (Li et al. 2019). The early twenty-first century witnessed acute energy shortages in some parts of China on account of underestimates of energy demand brought by the burgeoning economy, belated construction of coal, oil, electricity and other energy plants, and lack of transportation capacity. In the wake of the world financial crisis in 2008, the "RMB 4 Trillion stimulus package" (ten actions to spur domestic demand for steady and rapid economic growth) was rolled out, leading to a slight increase in energy consumption growth. But overcapacity also occurred in many industrial sectors, including metal smelting, chemical, and energy sector, with plants running below design capacity (Pan 2014). Since 2014, a

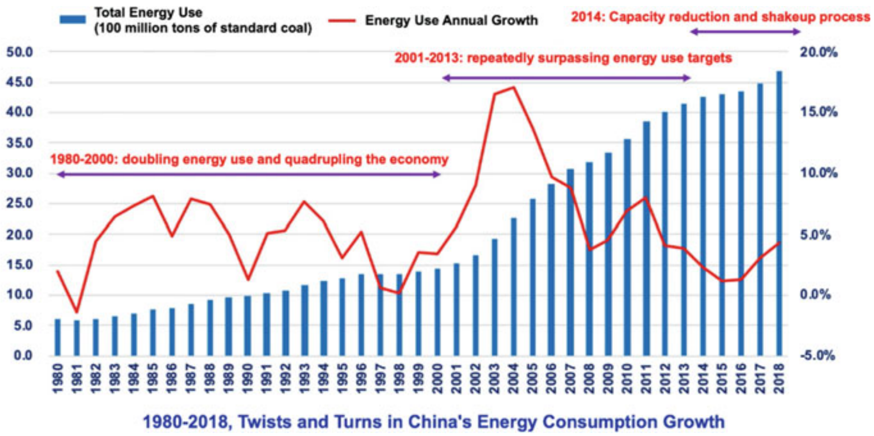

Fig. 1.6 Increase in energy use in China from 1980 to 2018 Li et al. (2019}

slowdown in energy demand growth and the energy mix adjustment had triggered severe overcapacity at coal and coal-fired power plants. At present, China's economy has shifted gear from the previous high speed to a medium-to-high speed growth, and high-quality development is the call of the time. Concrete steps must be taken to reduce energy waste from the mismatch between energy supply and demand.

Though the energy shortage in the early twenty-first century and the later oversupply appear to be at the opposite ends, the underlying causes are the same, that is, the failure to recognize the inherent relationship and regularity between economic development and energy demand in a timely manner, without forward-looking and proactively accurate adjustment. This underscores the inadequacy and deficiency of theoretical research on energy use control in China, and a severe mismatch between research on control theory, methods and strategies and realities on the ground.

To gain a scientific understanding of the way energy consumption grows in China, the author puts forward a theory of energy consumption growth from the perspective of construction-type energy use. Under this theory, total energy use in the society in any given period can be grouped into three categories: consumption, export and construction use, which correspond to the production or living activities for the purposes of end consumption, export and the fixed assets formation respectively. Among them, consumption and export energy use depend on the final consumption and export of the period, and are determined by the economic and social operation at that time. Though construction energy consumption is included in the total energy use of the society in a given period, the formation of fixed assets takes time, the construction energy consumption is invested in the current period, and the formed assets would lead to new production or service capacity in the future (Fu 2010). Therefore, the dynamic growth of energy consumption during rapid economic development is in fact driven by one-time, impulsive construction energy consumption.

Zhang (2019) Based on China's energy statistics for 2007, 2010 and 2012, the embedded energy status of final products is calculated, as shown in Fig. 1.7. It can

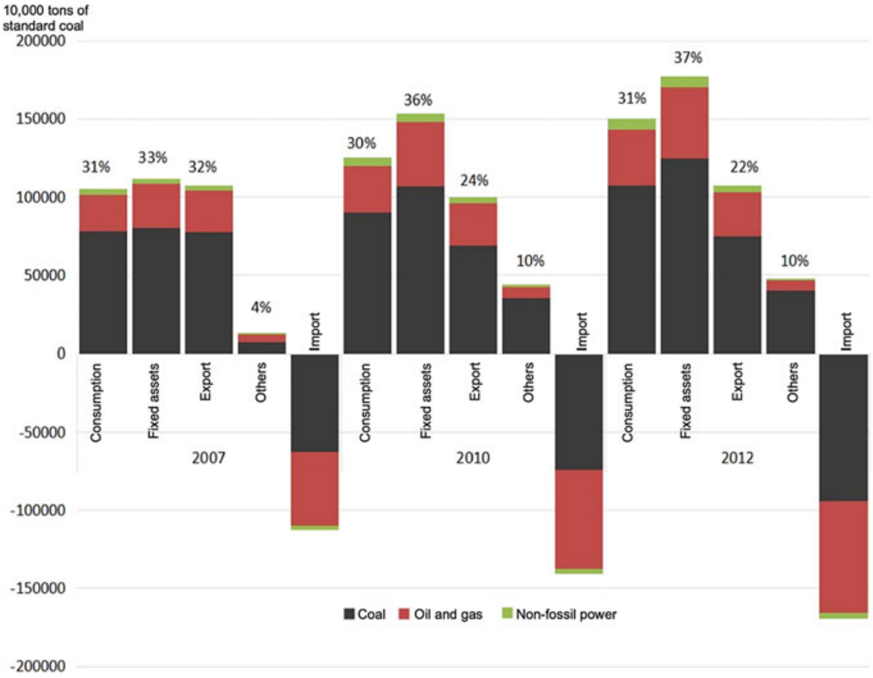

Fig. 1.7 Embedded energy of final products in China for 2007, 2010 and 2012 Zhang (2019)

be seen that during this period, the total embedded energy of all final products keeps increasing, while the embedded energy of fixed asset products always accounts for the largest proportion, which also shows an upward trend. This is largely because the huge investment in new infrastructure and industrial capacity after 2008 led to the production and installation of fixed asset products which consumed vast amount of energy, which was equivalent to large quantities of embedded energy in fixed asset products. By Zhang Xi's further calculation, among all the energy users in this period, the construction sector remained the one with the largest proportion of embedded energy in the final products, and it can be said that the high demand for construction services in China resulted in the great amount of embedded energy in the final products of the construction industry. Thus, if total energy use is to be curbed, a focus on the construction sector is essential.

The construction energy use from the construction sector is not only high in volume, but also considerable in terms of construction energy waste. Statistics show that in recent years, China's floor space has seen exponential growth, but building service life is well below that of developed countries, and the frequent demolition and construction of buildings has also implied tremendous energy waste. To deal with this problem, Fu Feng defined four scenarios with analysis based on the two set values of different per capita housing space demand and actual service life of houses. The key features are shown in Table 1.1(Fu 2010).

Table 1.1 Key features of the four scenarios Fu (2010)

Scenario definition	Baseline scenario	Policy scenario		
		S2 scenario	S3 scenario	S4 scenario
Increase in per capita housing space	No control	Control	No control	Control
Actual service life of houses	No extension (25 years)	No extension (25 years)	Extension (50 years)	Extension (50 years)

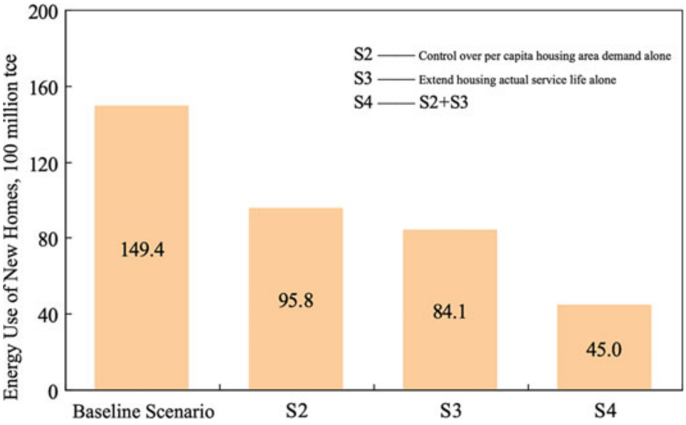

Fig. 1.8 China's cumulative construction energy use from new housing space from 2010 to 2050 Fu (2010)

From 2010 to 2050, China's cumulative energy use in building new housing space is shown in Fig. 1.8 (Fu 2010). Calculation of scenario S2, S3 and S4 finds that curbing the growth of per capita housing space demand and prolonging the actual service life of residential buildings would both slash increase of future energy use from residential housing construction, and the energy saving from extending life of residential buildings is even more promising. Besides residential houses, other fixed assets could also cut energy waste by extending life of assets and upping capacity utilization. These two approaches have become effective tools for energy use control.

The above research suggests that increasing utilization and service life of production capacity should be encouraged in China's future economic and energy planning. Besides, it's vital to align energy needs with economic development. More attention should be paid to the changes in the end consumption brought by economic development, as opposed to a sole focus on the current energy supply and efficiency, thereby ensuring a precise match between energy supply and consumption, and reducing construction energy waste.

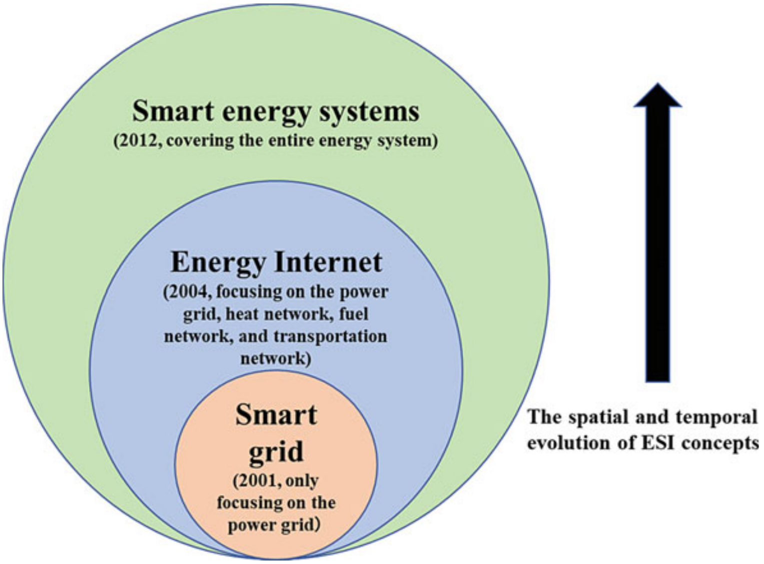

Fig. 1.9 Evolution of the notion of energy system integration

Energy and Infrastructure Coordination—Promoting Energy System Integration in a Cross-sectoral and Holistic Manner

The sound operation of energy system needs to be built upon the coordinated development of energy and infrastructure. Otherwise, the infrastructure would be abandoned prematurely or underutilized, and all range of production capacity connected by infrastructure would not be fully utilized, bringing about enormous energy waste. For instance, inadequate infrastructure in the fields of electricity peak regulation, transmission and distribution has accounted for tremendous curtailment in water, wind and solar in China, with substantial energy losses. Though more of China's non-fossil energy has been fed to the grid in recent years, water and wind curtailment still reached 69.1 billion KWH and 27.7 billion KWH respectively in 2018 (NEA 2019). Given a slew of energy challenges including climate change, China is bound to introduce more renewable energy and advanced energy-saving technologies to its energy system if it were to migrate from coal to non-fossil fuels, and from extensive energy consumption to high-quality and efficient energy use in the future. This puts higher demands for the smooth transition and efficient utilization of energy infrastructure, and requires guidance from new scientific approaches and methods.

With the progress of the third industrial revolution characterized by informationization, the rapid development and spread of information, communication and Internet technologies provide a new approach for integration to enhance the coordination between energy and infrastructure (Zhao 2018). Tracing the evolution of this approach (as shown in Fig. 1.9), one may find that the early concept of "smart grid" focused on the infrastructure optimization of the power system, which sought to optimize the integration and scheduling among different links of the power system with the aid of information and communication technology (Wang 2012). The subsequent emergence of "energy Internet" enlarged the scope of focus (Zeng et al. 2016). Though smart grid remained the centerpiece of the notion, it built stronger links among energy networks such as heat, fuel and traffic in terms of improved infrastructure integration. However, the energy Internet is mainly about open sharing among various energy networks, the infrastructure of each energy network is still relatively isolated. The notion of "smart energy system" emerged in recent years laid great stress on holistic optimization and cross-sectoral integration (Lund et al. 2017). The notion covers not only all energy networks, but also energy end users, including industry, building, traffic, etc. In terms of infrastructure, it highlights the integrated construction and operation of power grid, heating network and fuel network in the holistic perspective of the best match of all energy sources and end users, and strengthened system flexibility through a variety of energy storage modes. Given the above analysis, it's clear that the concept of smart energy system is more aligned with the future path of energy and infrastructure coordination, and smart grid and energy Internet can be viewed as the early stage of the path.

In light of China's unique energy system, the future of smart energy system must possess its own characteristics. According to literature review and reflections on China's reality, smart energy system in the country can be described as "a safe, flexible, economical, green, shared and coordinated sustainable energy system that enables the synergy of multiple energy forms through the holistic integration of energy supply and such other sectors of industry, building, traffic. It's grounded on the principle of cross-sectoral integration and systematic optimization, supported by the three pillars of smart grid, smart heating network and smart fuel networks, combined with flexible energy storage". With this in mind, the core of energy and infrastructure coordination is still the integrated construction and operation of the three core networks of smart grid, smart heating network and smart fuel network (see Fig. 1.10). All kinds of energy supply capacity (Fig. 1.10 above), energy end consumption and distributed energy (Fig. 1.10 below) should build energy hubs primarily for system integration, and achieve the optimal match of supply and demand through the three networks. As the gateway connecting energy production and consumption with the three energy networks, the energy hub guides and assist regional energy production to be fed into the grid, and provides smart energy services for users. Meanwhile, the hub seeks to facilitate multi-energy coordination and optimization of the overall system in a broader scope through the information and energy connectivity among varied hubs. In this model, flexibility of the overall energy system is critical, which brings the need for the flexible construction of varied energy storage facilities (lower right corner of Fig. 1.10). However, these involve the cooperation and coordination among different sectors and industries, and require the removal of barriers between sectors and industries. Thus, higher requirements are put forward for China's governance system and market mechanism.

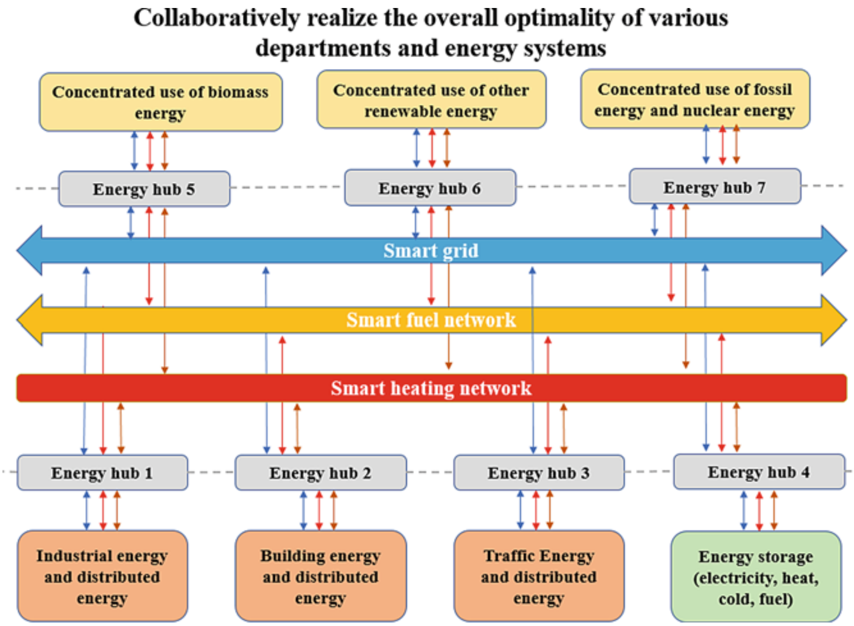

Fig. 1.10 Diagram of smart energy system

Energy and Regional Coordination—Enhance Regional Footprint and Work Sharing among Regions

Apart from the aforementioned problems at the national level, China's energy systems also vary greatly from region to region. However, existing national energy policies haven't accommodated regional disparities in this regard. During the 12th Five-Year Plan period, for instance, China set a binding target of a 16% reduction in energy intensity for nationwide implementation. A vast majority of provinces have made corresponding targets of 15–17%. But it turned out differently for different provinces. (see Fig. 1.11). This means that policy objectives should not be imposed in a broad-brush fashion. Without adopting a case-by-case approach, national energy policies would not benefit regional energy transition, and the national policy for energy transition might end up nowhere.

In order for the state to introduce region-specific policies to propel regional energy transition, a methodology of analyzing regional energy system with high technical accuracy is needed. The author adopts the EAA-LMDI method (Energy Allocation analysis-log Mean Divisia Index) in drawing the Sankey diagrams of energy distribution in provinces and municipalities in 2016 (as shown in Fig. 1.12), and conducted cluster analysis based on the characteristics of energy systems in each region. The figure reveals three stages from left to right: primary energy supply, intermediate cyclization and energy end use in each province and municipality. The color of the flow indicates the type of energy, and the width of the flow shows the amount of

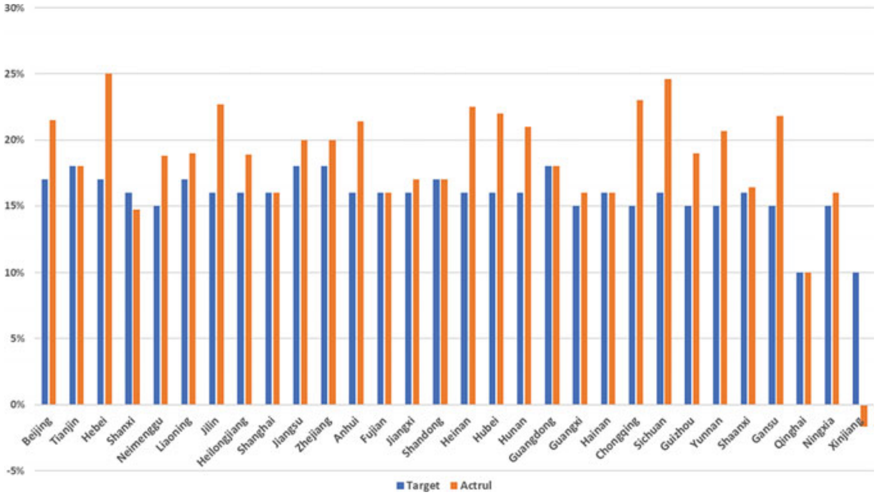

Fig. 1.11 Targets and results of lowering energy intensity in provinces and municipalities during the 12th Five-Year plan period

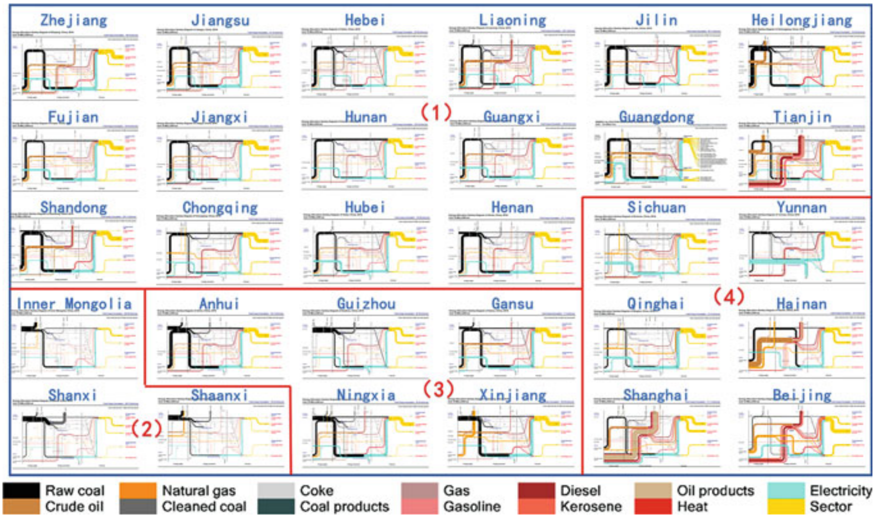

Fig. 1.12 Sankey diagram of energy distribution of provinces and municipalities in 2016

energy. The energy flow data enables analysis and calculation of the energy consumption growth of provinces and municipalities from 2011 to 2016. Based on the above research findings, the following conclusions can be obtained:

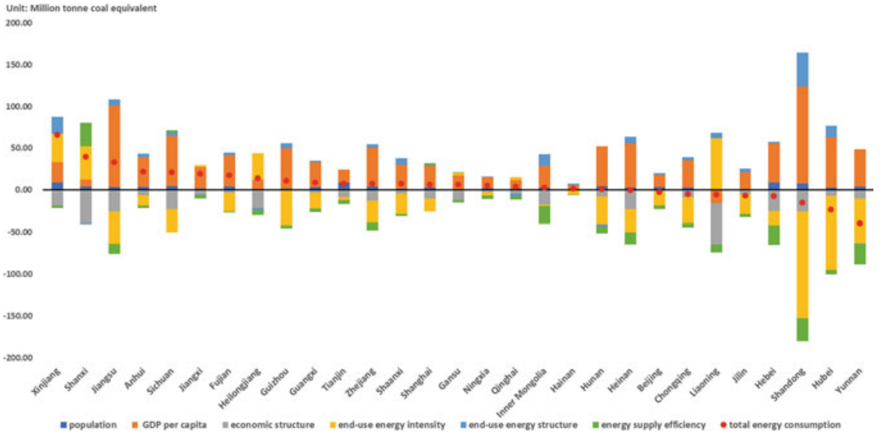

Fig. 1.13 LMDI decomposition of changes in energy use in the economy of provinces and municipalities from 2011 to 2016

1. **The coal development and utilization structure (shape of coal flow) best mirrors regional disparities in China's energy systems.**
   Energy systems of various provinces and municipalities can be grouped into four categories: (1) in the first category of energy system (Fig. 1.12, upper left), the coal flow resembles the Chinese character "儿", that is, coal is mainly supplied from outside, and is mostly used for electric heating production in energy conversion. 16 provinces and municipalities fall into this category; (2) in the second type of energy system (Fig. 1.12, lower left), the coal flow is shaped as "一", which indicates vast local production of coal and exports to other regions. The energy systems of three major coal producers fit this description, i.e. Inner Mongolia, Shanxi and Shaanxi; (3) in the third type of energy system (Fig. 1.12, lower center), the coal flow comes in the shape of Chinese character "乙", which refers to general self-sufficiency of coals in these regions with limited imports or exports. Xinjiang, Ningxia, Anhui, Guizhou and Gansu fit this category. (4) in the fourth energy system (lower right corner of Fig. 1.12), coal flow is not a major part of the energy system. The six regions produce and consume less coal, with other sources dominating the energy mix. For example, Beijing is mostly natural gas and electricity, Shanghai and Hainan see a high percentage of oil, and Sichuan, Yunnan and Qinghai are mostly hydropower.
2. **Per capita GDP constitutes the biggest driver of energy consumption growth in the economy of all regions.** Between 2011 and 2016, 20 out of the 29 provinces and municipalities saw increase of energy consumption in the economy. The LMDI decomposition analysis of the drivers of energy consumption growth is shown in Fig. 1.13. The red dots represent changes in the total energy consumption in the economic sector of each province over a five-year period, ranked from the highest to the lowest. The bar chart shows the changes in energy consumption caused by different drivers. In most provinces and municipalities, per capita GDP

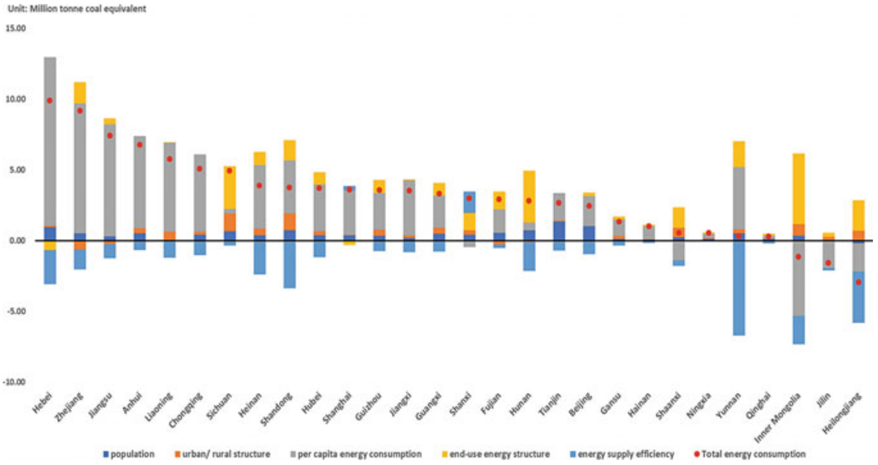

Fig. 1.14 LMDI decomposition of changes in residential energy use of provinces and municipalities from 2011 to 2016

is the biggest contributor to the growth in energy use, followed by population and end-use energy mix. The main inhibitors of energy consumption increase are economic structure, end-use energy intensity and energy supply efficiency. The adjustment of end-use energy mix is mainly manifested in the switch from coal to electricity. Energy consumption has grown as electricity is more responsible for primary energy consumption than coal. However, exceptions exist in a few regions. For example, the end-use energy intensity in Xinjiang and Shanxi and the energy supply efficiency in Shanghai have not been improved, which may have to do with the transfer of energy-intensive industries and underutilization of production capacity, etc.

3. **Per capita energy consumption is the most important driver for the growth of residential energy consumption in all regions.** From 2011 to 2016, 26 provinces and municipalities reported increase in residential energy use, as shown in Fig. 1.14. The red dots represent the total change in residential energy consumption in each region over the five years, ranked from the highest to the lowest. The bar chart shows the changes in energy consumption caused by different drivers. The most important driver is per capita energy consumption. Of all the drivers, only improvements in the efficiency of energy supplies have had a positive impact on curbing growth in energy use. It should be noted that although residential energy consumption only represents 1/7 of that in the overall economy, its growth is 3.5 times that of the economy (the national average). Therefore, the increase in residential energy consumption also warrants more attention.

The above research points to great disparities among various regions in China in terms of the status and trend of their energy systems, which calls for specific targets and paths of regional energy transition. In addition, the state should explore

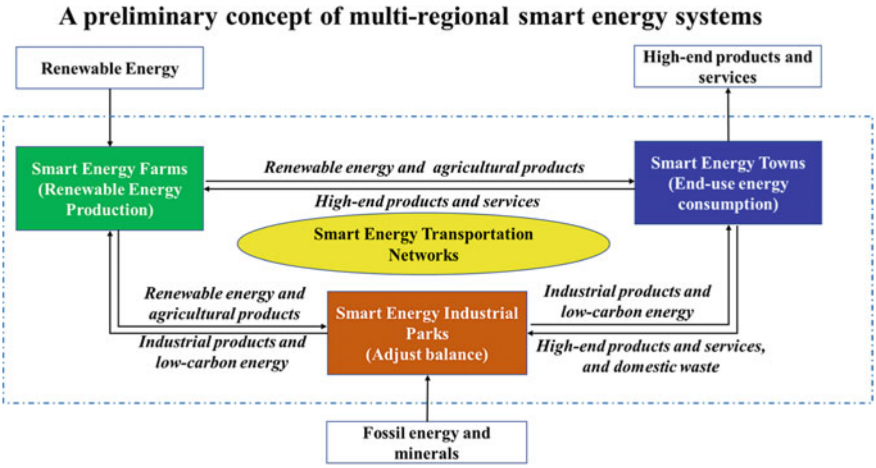

Fig. 1.15 Diagram of the new approach for energy system integration that accommodates three coordinations

innovations in regional energy governance and market management in light of the administrative segmentation and market characteristics of each region.

New Approach for China's Energy System Integration as Required by "Three Coordinations"

The three coordinations of energy and economy, energy and infrastructure, and energy and regions is not isolated from each other, but interconnected and interactive, and should be advanced in a coordinated manner. In this connection, the author proposed the coordinated development notion of "smart energy farms—smart energy towns—smart industrial parks—smart transportation network" under the requirements of the three coordinations (see Fig. 1.15) in an attempt to provide a new solution for energy system integration during low-carbon energy transition.

As far as this approach is concerned, smart energy farms, smart energy towns and smart industrial parks are both energy producers and consumers. Yet they stand to perform different main functions, serving as producer, consumer and regulator of supply and demand in the overall energy system. Specifically, smart energy farms combine renewable energy and agricultural production to supply clean energy and agricultural produce; smart energy towns import large quantities of energy and materials to meet the needs of people's life and work; smart industrial parks are where the production and storage of fossil energy and energy-consuming products are highly concentrated, and seek to balance supply and demand of the energy system. The three share and collaborate with one another in terms of energy and information through the energy hub in the smart energy system:

(1) Smart energy farms are mainly distributed in remote areas rich in renewable energy, where small populations and relatively low land costs make them suitable for massive development and export of renewable energy and agricultural production (see Fig. 1.15). To ensure the stability of energy output, local industries and energy storage devices that flexibly absorb renewable energy can be developed to generate additional income other than agriculture. Smart energy farms boast pleasant ecological landscape, which meets people's demand for a decent eco-environment;

(2) Smart energy towns are where population, high-end manufacturing and service industry concentrate, which entail import of vast amount of energy, products and materials from the outside to meet the needs. By promoting electrification and end-use energy saving in cities and towns and improving energy efficiency, some distributed energy storage devices can also assist in the regulation of energy supply and demand. With no polluting industries and imported electricity as the primary form of energy, smart energy towns would be livable places where people enjoy high-end products and services and live out their dreams for a better life;

(3) Smart industrial parks are mostly located in the proximity of mineral mines and existing industrial parks. Each park gathers many energy-intensive industries on one or more industrial chains. Starting from the production of fossil energy, the smart industrial parks achieve the high-quality and high-density use of materials and energy within a small circle. Through smart management and regulation, the parks oversee the production and storage of fossil energy and energy-intensive products to ensure the balance between energy supply and demand. Smart industrial parks can also receive and dispose of waste from cities and towns. In the park, products of the upstream industry are used as materials for the downstream. The by-products of some industries could be utilized by others. High temperature exhaust gas from power or steel plants can serve as sources of heat for other industries, achieving recycling and co-development of energy and material. Thanks to the smart management and full use of materials and energy, smart industrial parks minimize the negative impact on the environment and protect the living environment of the park residents.

Smart energy farms, smart energy towns and smart energy industrial parks are connected by "smart transportation network", which not only includes the transportation of non-energy products and people, but also transportation of all forms of energy. Smart transportation network requires the integration of passenger and freight transportation network and energy network to realize the optimal design and operation of transportation infrastructure.

The vision of "smart energy farms–smart energy towns–smart industrial parks–smart transportation network" accommodates the "three coordinations": (1) taking into account technology switch in the space of energy, industrial upgrading in the space of economy and eco-environment protection. In particular, a match between energy technologies and local industries is ensured when designing the three "smarts" to satisfy people's quest for better life; (2) sitting on top of the full use of existing production capacity and resources of each region, stressing clear regional division of labor and cooperation to bring out comparative advantages, and guiding and improving transportation infrastructure network; (3) bearing in mind the status quo and disparities of regional energy development, and putting forward the plan for energy system integration on a case-by-case basis. In theory, the envisioned energy system not only fits in with the current requirements of carbon emission cut and sustainable development, but also future mandates for zero or even negative carbon emission. However, this notion is now a mere scientific assumption and a system-wide proposition, and merits more research and practice to verification.

1.4 Requirements and Suggestions for Energy Governance and Energy Market to Fulfill the "3+1" Vision

With the future path of the energy system proposed in Sect. 1.1.3, a new framework of energy governance is needed to introduce strategy and policy that are to be implemented in the energy market so as to secure low-carbon transition of the physical energy system. In particular, the novel approach of "3+1" energy system integration would pose new challenges to China's existing energy governance and energy market model. The following section would put into perspective the main challenges for the current system in light of the current energy governance and energy market in China, and provide policy suggestions.

1.4.1 Challenges for Energy Governance and Energy Market Brought by "3+1"

1.4.1.1 Fragmented Authority Renders Integrated Governance Difficult

The functions of China's energy governance are currently split among a dozen government agencies, which involves consultations among them when it comes to major energy issues. The "3+1" approach would require involvement of more functional agencies to devise energy planning and exercise governance. Therefore, the primary challenge for China's energy governance is to coordinate a range of government authorities in promoting energy system integration, tackling climate change while advancing low-carbon transition of the energy sector.

1.4.1.2 The "Top-Down" Management Approach Hampers Innovation

A vertical hierarchy has long characterized China's energy management. The drawback of the "top down" approach is: when dealing with such complex and enduring energy governance issues as the “3+1”, the multiple layers of the organizational pyramid would undercut government enforcement, however strong it might be in the first place. And information and decisions, when passing through the layers, tend to be stalled or lost. Consequently, policies made at the central level might be divorced from the realities on the ground. What’s more, energy consumers, citizens and small businesses find it hard to engage in energy governance. Some localities and enterprises have been constantly at the receiving end of mandates from above, without any incentives to carry out policies of their own accord. Worse still, some promising local innovation, suppressed by the hierarchy, has remained untapped.

1.4.1.3 Sectoral Barriers Impede Collaboration

China’s energy market was once marked by high monopoly and high market regulation. Despite decades of reform, some market players and industries are still preoccupied with local interests and gains, hindering extensive cross-industry collaboration required by “3+1”. Furthermore, government still maintains the grip on prices of some energy products, and resources could not be best allocated via price lever. In addition, private investment has limited access to certain energy projects, which impedes the development of new energy and distributed energy.

1.4.1.4 Inadequate Information Management System Impairs Cross-Disciplinary Interaction

The “3+1” model, in governing and managing the emerging sector, could not be materialized through expertise from a single discipline. Rather, it involves cross-disciplinary, cross-industry and cross-sector issues that require tremendous knowledge sharing, interaction and communication, presenting a huge challenge to the coverage and efficiency of existing information management system. This, in part, explains the rapid development of various energy think tanks in China in recent years.

1.4.2 Policy Suggestions on Guaranteeing “3+1” Energy System Integration

1.4.2.1 Empower Energy Planners and Strengthen Leadership and Cross-Sector Coordination

Planning and research entities of energy strategy at the central and local governments should be bestowed a level of leadership and authority that can handle such complex, key energy system integration models as “3+1”, in order to coordinate and integrate the current separate functions scattered in various government departments, and maximize China's institutional superiority of "pooling resources for grand projects". What's more, energy researchers and planners should promptly produce a national strategic plan for coordinated development of energy and economy, energy and infrastructure, and energy and regional development similar to the "3+1" notion, and facilitate the establishment of region-specific smart energy systems and the creation of effective linkage among them.

1.4.2.2 Step up Modernization of Energy Governance System and Capability and Invigorate Synergistic Innovation

The central government should follow the needs of the "3+1" approach by appropriately decontrolling authority, encouraging local governments, enterprises and the public to actively engage in energy governance, thereby forming a multi-stakeholder consultation mechanism that blends top-down and bottom-up approaches. In doing so, special attention should be paid to address the disconnect between central level decisions and the actual needs of local governments, enterprises and citizens, and enhance the interaction between the central government and various stakeholders. With these steps, local governments, enterprises and the people would be incentivized to proactively drive local innovation in the interest of the whole nation.

1.4.2.3 Expedite Reform of Energy Market and Energy Supply and Build Energy Companies into Comprehensive Service Providers

The "3+1" approach calls for prompt removal of industry barriers and enhanced cooperation and business integration among sectors in order to pay the way for the development of various smart energy systems. The Chinese government should relax price controls and help industries and enterprises to break down barriers, with an aim to build integrated energy service providers that run a variety of energy operations, both upstream and downstream, and encourage the development of innovative small and micro energy businesses. Key support and encouragement should be offered to enterprises that integrate multiple sources of energy and energy needs, or regional energy hubs.

1.4.2.4 Build Stronger Energy Information Management System to Ensure Open and Smooth Communication

Align with the "3+1" approach, comprehensively strengthen energy management information systems at all levels and in all sectors, industries and regions to enhance the accuracy, openness, timeliness, transparency of information, and attach greater importance to the dissemination of information. In the meantime, actively promote various energy-specific think tanks that seek to address climate change and sustainable development, and support their cooperation with local governments, enterprises, civil society and the international community.

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Chapter 2
Research on Urbanization and Low-Carbon Development in China

Jinxi Wu and Hui Zhao

Abstract Urbanization, industrialization and modernization well complement one another. In light of economic development, urbanization meets the demands of industrial production for labor, infrastructure, industrial chain, and low cost transport. On the other hand, rising urban population would spark a number of social issues, including traffic jams, shortage in educational and medical resources, environment pollution, and especially climate change, which has triggered worldwide concern. As one of the world's largest carbon emitters, China will bear the dual impact of accelerated urbanization and the obligation of vast emission reductions for a long time to come. This chapter centers on the challenges of low carbon development during urbanization, providing thorough diagnoses of the characteristics and interactions of urbanization and carbon emissions, exploring the way urbanization impacts carbon emissions, performing research on the regional differences of how urbanization affects carbon emissions, and the size and pattern of future Chinese cities, thus providing theoretical support to the urbanization strategies and policies for energy conservation and emissions reduction that accommodate low-carbon development.

Keywords Low-carbon development · Urbanization · Carbon emissions · STIRPAT model

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2.1 Challenges for Low-Carbon Development During Urbanization in China

2.1.1 The Relationship Between China's per Capita Carbon Emissions and per Capita GDP is Still Unstable

Urbanization in developed countries was driven by industrialization in the eighteenth century and was largely completed in 1970. The first industrial revolution, set off in the later half of the eighteenth century, marked the dawn of modern industrialization. The mid twentieth century saw the start of the second industrial revolution, which sped up industrialization in Europe and the United States, worsening the ecological environment from production activities as economies took off (Jiagui et al. 2008). Many deadly environmental incidents occurred during this period, including the dirty smog in Los Angeles in the 1940 s, the killer fog in London in 1952, and the minamata disease in Japan in 1956. The experience of developed countries reminds us that when industrialization reaches a certain level, especially at the late stage, the tensions between economic and social development and eco-environment would aggravate and even turn to a full-blown crisis.

The level of China's urbanization has surged from 10.64% in 1949 when PRC was founded to 60.60% in 2019, averaging 1.4% growth year-on-year. Permanent urban residents have spiked from 40 million to 930 million in the past 7 decades, a net increase of 750 million. The scale and speed of this urbanization have never been seen in the world, and have exerted dramatic impact on China's economic growth, social development and ecological environment. Examples abound for environment worsening during this period, including the continuous outbreak of blue-green algea in Taihu Lake, Chaohu Lake and Dianchi Lake in 2007, the chromium residue pollution in Qujing, Yunnan province in 2011, the cadmium pollution in Longjiang, Guangxi in 2012, and the growing smog in north China since 2012.

In the context of global battle against climate change, low-carbon development is imperative. To define the relationship between economic development and eco-environment in the process of urbanization, the author chose China, the United States, France, Germany, Japan and South Korea as the objects of research to draw the diagram depicting relationship between per capita GDP and per capita CO_2 emissions in these countries.

Figure 2.1 reveals three distinct phases of per capita CO_2 emissions as economies developed. The first phase saw rising emissions. The growth in per capita CO_2 emissions was proportional to that of per capita GDP. The second phase marked a stablizing period, where per capita CO_2 emissions remained stable without a sharp increase, despite the continuous growth of per capita GDP. The third phase showed a decline in per capita CO_2 emissions even though the per capita GDP were on the rise.

The diagram suggests that the United States, Germany and France have passed the periods of rising and stablized per capita CO_2 emissions. Starting the twenty-first

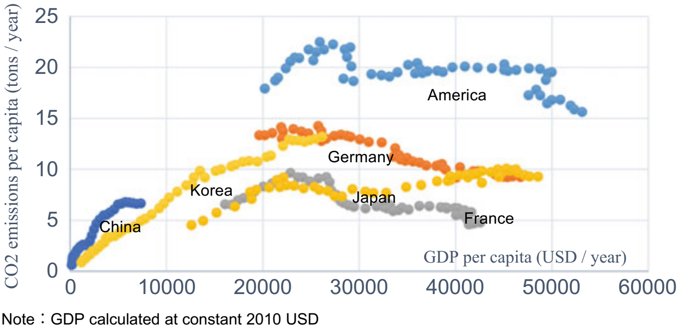

Fig. 2.1 Relation between GDP per capital and CO_2 emissions per country *Data source* World bank database

century, the per capita CO_2 emission has been decoupled from the per capita GDP and has been falling ever since. In the wake of a soaring peiord, Japan's per capita CO_2 emissions have gradually stabilized, but a downward trend is yet to emerge. South Korea is still in the middle of rising CO_2 emissions per capita as well as GDP per capita, so is China.

2.1.2 China's Vast Energy Use Adds Difficulties to Low-Carbon Development

The size of a country's energy consumption determines the level of difficulty in energy transition and low-carbon development. The analysis of the changes in total primary energy consumption of different countries finds that China has overtaken the United States since 2009 to top the ranking of energy use. Such massive transformation of a country's energy system is unparalled in the world (Dan et al. 2018).

Figure 2.2 shows that energy consumption of developed countries has been fluctuating in a stable manner, but the increase in China's energy use can be divided into two stages. From 1965 to 2001, the increase of energy consumption was slower, with the annual growth of total primary energy use averaging at 5.9%. 2001–2018 saw faster rise in energy consumption, averaging 7.4% year-on-year growth in the total primary energy consumption. The soaring energy use in China after 2001 is partly due to the growing urbanization after China's accession to the WTO in 2001, which pave the way for China to become the world's factory, hence its huge industrial capacity and increased energy consumption.

In the process of urbanization in developed countries, eco-environmental protection, energy security and climate change tend to occur at different stages. Thus, targeted policies and plans could be formulated in each country to promote restructuring of its energy system, and tackle problems in each of the stages. In contrast, eco-environmental protection, energy security and climate change emerged at the same

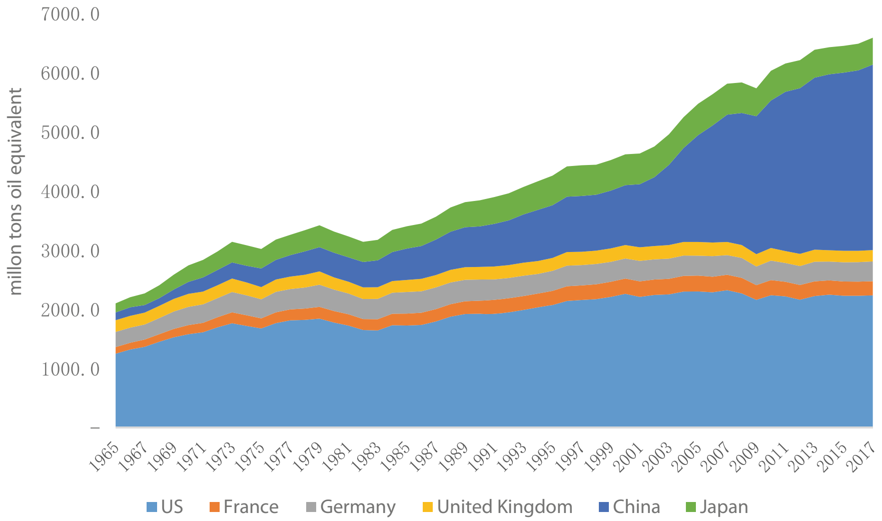

Fig. 2.2 Changes in primary energy consumption by country *Data source* World bank database

time in China. Some Chinese cities are plagued by rampant air pollution, making the case for urgent actions for the sake of the environment. To combat climate change, China has committed to peak CO_2 emissions around 2030 and strive for an early peak, with CO_2 emissions per unit of GDP down 60–65% in 2030 from the level in 2005 (Jiankun 2013). China has assigned itself a rather complex task to juggle improvement in the ecological environment, growth in urbanization and the fight against global climate change. And no case study can be found in the world history of energy transition.

2.1.3 *China Faces Greater Environmental Pressure Compared to Developed Naitons Given the Same Size and Level of Urbanization*

Due to China's vast territory and tremendous regional disparities, the level of urbanization in the eastern part of the country has exceeded 50%, some areas have even surpassed 80%. But the central and western regions are still seeing rapidly growing urbanization. The author selected Chinese regions with a high level of urbanization, including Yangtze River Delta, Pearl River Delta and Bohai Rim Region to compare against France, Britain and Germany in their 1950–1982 period, based on energy intensity per unit of land area, as shown in Fig. 2.3. The Yangtze River Delta, Pearl River Delta and Bohai Rim Region cover 210,700 km^2, 335,100 km^2 and 375,100 km^2 respectively, which are close to the land area of France (549,000 km^2), Germany (356,900 km^2) and the United Kingdom (243,600 km^2). Yet great disparities can be

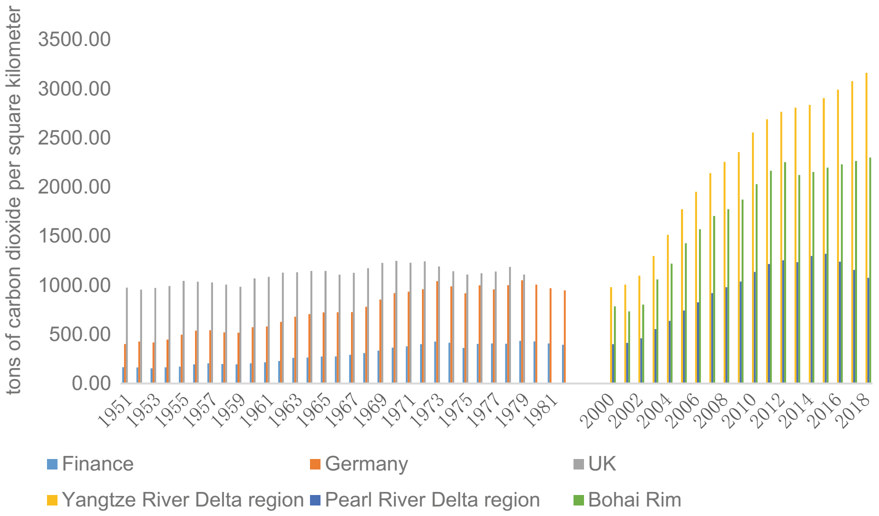

Fig. 2.3 Energy consumption by region *Data source* World bank database

found when comparing the energy intensity per unit of land area between the Chinese regions and the three European countries. Energy intensity per unit of land area in Yangtze River Delta and Bohai Rim is much higher than that of Britain, France and Germany. The figure of the Pearl River Delta is close to that of the UK and Germany, but higher than that of France.

China's Yangtze River Delta, Pearl River Delta and Bohai Rim Regions also showed rapid growth in CO_2 emission intensity per unit of land area, which has surged since 2003. The highest CO_2 emission intensity per unit of land area in the history of England is found in 1973 at 294.82 tons of carbon dioxide per square kilometers. China's Yangtze River Delta and the Bohai Rim Region have surpassed UK in 2001, so have the Pearl River Delta in 2007.

2.1.4 Lock-in Effect from China's Gigantic Industrial Production Capacity and Infrastructure

Since its entry to the WTO in 2001, China has gradually earned the moniker of "factory of the world". Its huge industrial production capacity, especially high energy-consuming industries of steel, cement, and automobile production have seen continuous growth. Iron and steel output grew from 107.37 million tons in 1965 to 1.049588 billion tons in 2017, with an average annual growth of 4.48%; cement output climbed from 536 million tons in 1965 to 2.3367908 billion tons in 2017, growing at 2.87% on an average annual basis; automobile production went up from 1.63 million in 1965 to 29.801 million in 2017, averaging 5.69% of annual growth (Fig. 2.4). China's indus-

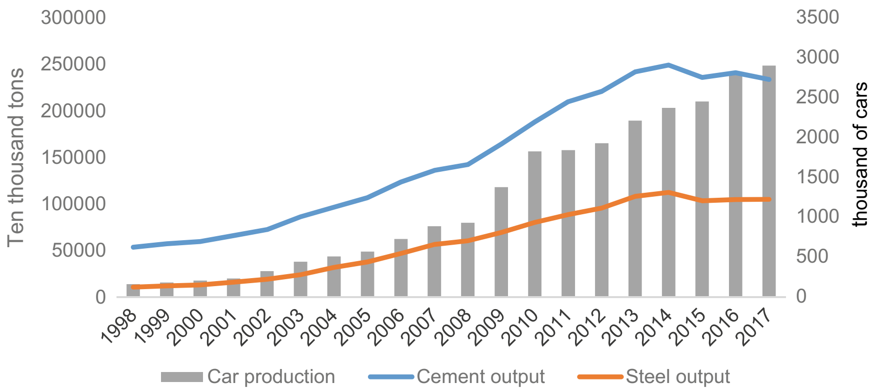

Fig. 2.4 China's steel, cement and automobile output *Data source* National statistics bureau

trial pollution account for more than 80% of the country's pollution from energy use, and high-energy-intensity industries made up over 90% of industrial pollution.

The urbanization process entails massive infrastructure construction, and investment in this regard would give rise to energy consumption. The "lock-in effect" of capital and technology is hard to disappear in the short term (Ni Weidou et al. 2015). China's manufacturing industry is relatively fragile, and its current round of rapid expansion is nothing short of copying conventional technologies. Once investments are made in the technologies for infrastructure, machinery and large durable consumer goods, their life would last from 15 to over 50 years and would not be easily scrapped before they run out of life. According to IEA estimates, from 2006 to 2030, China would invest $3.7 trillion in the energy sector, 74% of which would be spent in electricity, especially thermal power. The high carbon lock-in in China testifies to its large heavy chemical industry, which is hard to reverse any time soon.

To sum up, China is undergoing the largest and fastest urbanization in the world history. Growing urbanization, while opening a new chapter of sustained economic growth and social development, has disturbed the low level of harmony and symbiosis between humans and eco-environment back in the agricultural civilization, creating glaring environmental and ecological problems. To strike a balance between economic growth and environmental protection, it's vital to thoroughly assess the characteristics and the interaction between China's urbanization and carbon emissions in different stages based on national conditions, explore the way urbanization impacts carbon emissions, study the regional disparities of how urbanization affects carbon emissions and other key issuess, thus providing theoretical support to the urbanization strategies and policies for energy conservation and emissions reduction that accommodate low-carbon development.

2.2 Analysis on Historic Evolution of Urbanization and Carbon Emissions in China

2.2.1 Urbanization and Carbon Emissions Since Reform and Opening up

Since the reform and opening up, China's urbanization has maintained a sound development. The burgeoning China's economy has fast-tracked its growth, surging from 17.9% in 1978 to 60.60% in 2019. Its permanent urban population had soared from 172 million to 831 million, accounting for about 26% of the world's new urban population in the same period. Figure 2.5 suggests that the urbanization in the world's major developed countries, i.e. the United States, the United Kingdom and Germany, was growing much slower than that in China during the same period from 1978 to 2018. Meanwhile, Japan and South Korea have increase by nearly 20% and 30% respectively. But urbanization growth in South Korea has cooled down significantly after 1997, and the same was true for Japan after 2009. Despite a slowdown or gradual slowdown of urbanization in the world's major developed countries from 1978 to 2018, it had still remained above the world average. In 2012, China's urbanization exceeded the average level of the world and has kept robust growth ever since.

To better understand urbanization development in China, one can divide it into three stages since the reform and opening up, with 30 and 50% as the demarcations (Jianjun and Zhiqiang 2009).

1978–1995 marks the first stage, or the infancy of urbanization development that began to gather momentum, which was mainly featured by growth in the urban periphery, as the country embarked on reform and opening up and made initial progress towards its goals. During this period, the level of urbanization rose from 17.9% to 29%, close to the 30% cut-off, averaging 0.65% growth on a yearly

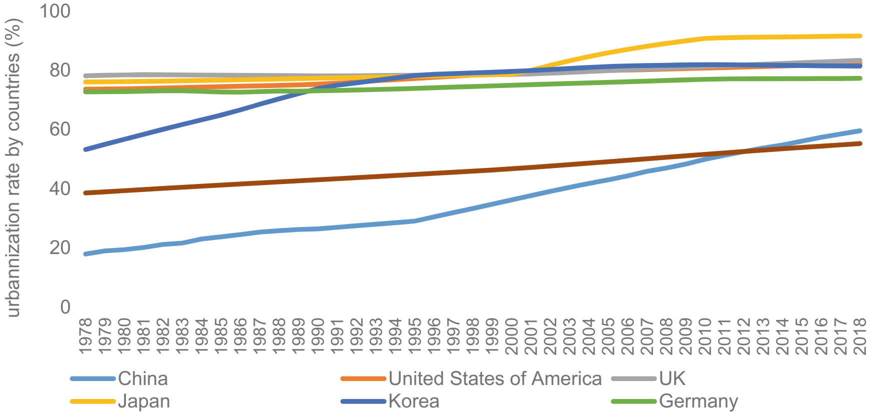

Fig. 2.5 Urbanization in major countries *Data source* World bank database

basis. The second stage refers to the rapid advancement period from 1995 to 2010, which saw the transition from local urbanization to migration urbanization, when the country has initially put in place and improved the socialist market economy. And urbanization jumped from 29.0% to 50.0%, reaching the 50% demarcation, up 1.39% on average year-on-year. The third stage lasts from the end of 2010 to now, with fast growth and slight slowdown, when local and migration urbanization developing in tandem amidst all-out further reform in China (Li & Cai 2015). Urbanization grew from 50.0% to 59.58% during this period, registering an average yearly growth of 1.2%, slightly down from the previous stage.

From 1978 to 2018, China's carbon emissions soared from 14,62,168,600 tons to 9,428,795,300 tons, an increase of 6.45 times and an average annual growth of 4.9%, indicating a spike in carbon emissions as reform and opening up unfolds. As the world's largest carbon emitter, China produces much greater emissions than major developed countries such as the United States, the United Kingdom, France, Italy, Japan and South Korea, and also greater than that of India, the world's second most populous country, which is also a developing one. Figure 2.6 shows that UK, France, Italy, Japan and South Korea experienced fluctuations and an overall increase in their national carbon emissions from 1978 to the present. The 2009 Copenhagen Climate Change Conference triggered a decline in emissions in many countries. During the same period, carbon emissions in the United States fluctuated and rose from 4,306,674,850 tons in 1982 to 5,789,305,000 tons in 2005, and began to fall around 2009. However, the trend was reversed after the United States announced its withdrawal from the Paris Agreement in 2017. Carbon emissions in India, the world's second most populous country and a developing one, has been on the rise as a whole, but the growth is slow. The growth curve of India's carbon emissions from 1978 to now is similar to that of China before 1978.

Given the analysis of China's carbon emissions, it can be divided into three stages based on its growth and proportion in the world's carbon emissions. The

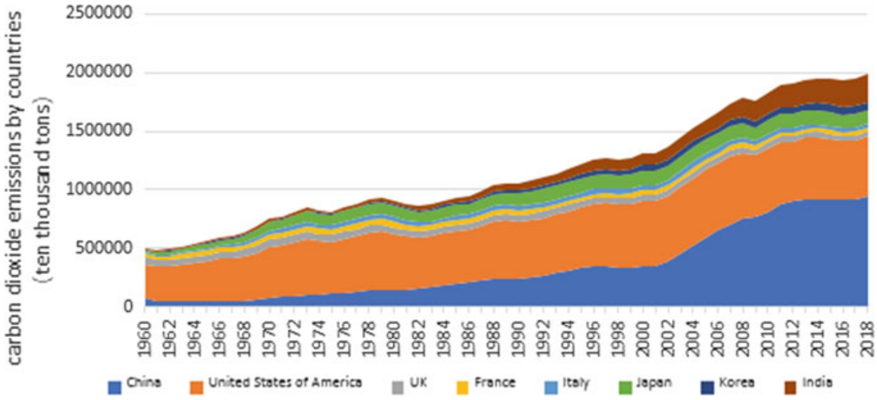

Fig. 2.6 Carbon emissions in major developed and developing nations *Date source*: BP official website

first stage is the initial growth period of 1978–1999, which saw the dawn of China's reform and opening up and initial progress on this front. Carbon emissions rose from 1,462,168,600 tons in 1978 to 3,318,055,600 tons in 1999, with an average annual growth of 4.18%. The second stage is characterized by a spike in emissions from 2000 to 2011, when China created and consilidated its socialist market economy, prompting massive infrastructure construction and economic takeoff. Carbon emissions surged from 3,405,179,900 tons in 2000 to 8,805,881,200 tons in 2011, up 9.97% on average on a yearly basis. The third stage witnessed the volatile emission reduction from 2012 to 2018, as China's economy moved into a "new normal" phase, pursuing sustainable, green and ecological development. Carbon emissions fell to 9,119,016,200 tons in 2016 from 9,237,771,300 tons in 2013, down 1.29%. Policies for capacity reduction and air pollution control began to work.

2.2.2 Historic Interactions Between China's Urbanization and Carbon Emissions

As mentioned above, the evolution of both carbon emissions and urbanization can be divided into three stages, as the two similar development and changing patterns, which implies certain interaction and correlation between them. Environment Kuznets Curve suggests that in the early stage of urbanization when economic is relatively fragile with small industrial and residential energy use, energy consumption tends to rise slowly, so do CO_2 emissions; When urbanization accelerates, economy would quickly expand and push up total energy use and CO_2 emissions, driven by ballooning investments and consumptions; and in the later stage of urbanization, the changed growth model would reduce the dependence on energy, leading to a decline in energy use and CO_2 emissions.

Specifically, urbanization marks the complementary development of industrialization and modernization. Therefore, the research on the relationship between urbanization and carbon emission in China should take into account the role of industrialization.

Stage one: when China set in motion reform and opening up, both urbanization and industrialization was at low levels. The implementation of major decisions concerning reform and opening up opened up a new chapter of growth for thermal power. In the 6th Five-Year Plan, the central government proposed to "build thermal power plants and bases in regions rich in coal resources. If transportation allows, such plants should also be built in regions scarce in coal but burdened with great electricity use." In 1985, the state council issued the *Interim Provisions on Encouraging Financing of Electricity Industry through Fund-raising and the Implementation of Tiered Electricity Prices*, encouraging diversified investment in power production, and gradually relaxing its regulation over the industry, which proved to propel the development of the industry, especially thermal power. In 1992, Deng Xiaoping's southern tour speech and the 14th National Congress of the Communist Party of

China put China's economic reform on the track of market economy, under which Chinese steel enterprises gradually crafted new path of development through fund-raising in the capital market. As a result, production of coal and steel was in full swing, ensued by soaring CO_2 emissions.

Stage two: China's accession to the WTO in 2001 paved the way for the rise of China as the factory of the world. Its phenomenal industrial production capacity, especially that of energy-intensive industries such as steel, cement and automobiles, has been ramping up. Investment in the secondary industry shot up from 1.6628 trillion yuan in 2003 to 10.1013 trillion yuan in 2010, an increase of 6.08 times, which spawned a constant string of large industrial enterprises. In 1999, there were 83,738 large light industry enterprises and 81,342 big heavy industry enterprises, each making over 5 million yuan a year. Fast forward to 2010, 188,040 light industry businesses and 264,832 heavy industry businesses have reported yearly revenue of over 5 million yuan, up 2.25 times and 3.26 times respectively. In addition, growing urbanization has exerted mounting pressures on energy and transportation. Per capita residential energy use surged from 42.4 kilowatt hours in 1990 to 383.1 kilowatt hours in 2010, an increase of 9.04 times. The total length of highways climbed from 1.6798 million km in 2000 to 4.1064 million km in 2011, up 2.44 times. The total length of expressways rose from 16,300 km in 2000 to 84,900 km in 2011, a growth of 5.21 times. The expansion of industrial investment, rising number of industrial enterprises, and skyrocketing housing construction areas made for a sharp increase in carbon emissions.

Stage three: In 2012, China's economy entered a phase known as the "new normal", as the 18th National Congress of Communist Party of China (CPC) set the goal of promoting ecological civilization and its coordinated progress with politics, economy, culture and society, or the "five-in-one" strategy. Eco-civilization has been put high on the agenda; eco-environmental security has become a social consensus; and the notion of "green mobility" has been reaffirmed and prioritized. The Third Plenary Session of the 18th CPC Central Committee made the proposition of low-carbon development and ecological protection. Premier Li Keqiang stressed the need of strengthening rules and regulations to preserve the environment, overhauling and innovating China's transportation industry to reduce waste and emissions, and creating a new norm of using institutional constraints for environmental protection. In 2017, the Report to the 19th National Congress of CPC identified "resource conservation and environmental protection" as basic state policy, upholding the philosophy of "green is gold" to ensure the harmonious coexistence between man and nature. In February 2017, the General Office of the Central Committee of CPC and General Office of the State Council distributed *Several Opinions on Demarcating and Keeping the Red Line for Ecological Protection*, urging and supervising local governments to perform eco-environmental protection, and holding local party committees and governments accountable for this effort. The document also requested scientific demarcation and more stringent protection of ecological red lines through a blend of "top-down and bottom-up" approaches whereby governments provide direction for local implementation. A toolkit of control measures and incentives for ecological protection should also be developed. To follow up with the mandates, central and local governments worked together to shut down a great many enterprises that were energy intensive, highly polluting and with low capacity, and rampped up investment in pollution treatment and ecological improvement. These policies proved to be effective in driving energy conservation and emission reduction.

From the regional standpoint, urbanization in east China is relatively fast, especially in some coastal areas, which saw a high level of urbanization. Cities like Shanghai and Guangzhou have even come to the later stage of urbanization. In contrast, the central China is trailing way behind, despite the relatively high urbanization level in some economically developed cities or regions. West China, due to its mostly poor natural conditions, fares much worse in this regard, with only a handful of exceptions (Houkai 2014). After reform and opening up in 1978, the per capita GDP of the east grew considerably faster than that of the central and western regions, and that of the central region was faster than that of the west. East China got a head start in its development thanks to its geographical location at the coast, attracting a large number of industrial enterprises. As the region flourished, it came to lend a helping hand to its central and western peers. Starting 2000, central China has witnessed a declining proportion of its primary industry, and its secondary industry exceeded 50% of local GDP in 2008. West China also underwent industrial restructuring, with the share of the primary industry falling gradually. But its secondary industry has never passed the 50% mark. In a word, the level of urbanization in China is marked by a tiered pattern, higher in the eastern region and lower in the west, which corresponds to the greater carbon emissions in the east and less emissions in the west. This is largely consistent with the geographical distribution of China's economic development.

2.2.3 Future Trend of China's Urbanization and Carbon Emissions

The National Plan for a New Type of Urbanization (2014–2020)[1] indicates that China's urban share of population would hit 60% by 2020, a goal that has been attained ahead of time in 2019. By the end of 2019, 60.60% of China's population lived in cities, which translated to 848.43 million permanent urban residents, an increase of 17.06 million over the previous year. The number of rural residents stood at 551.62 million, 12.39 million less than that at the end of the previous year. At present, a gap still exists between urbanization in China and that in major developed countries. Over 90% of Japanese population are urban dwellers, over 80% in the United States, and around 75% in Germany. According to the *17th Report on China's Urban Ccompetitiveness*[2] issued by the National Academy of Economic

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[1] In March 2014, The CPC Central Committee and State Council issued *The National Plan for a New Type of Urbanization (2014–2020).*

[2] In June 2019, CASS and Economic Daily jointly released the *17th Report on China's Urban Ccompetitiveness* issued by the National Academy of Economic Strategy of CASS.

Strategy of CASS, China's urbanization will continue to grow in the future, with an estimate of over 70% urban population by 2035. Urban migration will be turned from individual to family movement. More people will migrate from individuals to families. In addition, *the Economic Blue Paper: China's Economic Growth Report (2018–2019)*[3] pointed out that urban residents will represent about 80% of China's population by 2050, which will require as many as 1,050 small and medium-sized cities with less than 500,000 people. This means that despite the slowdown in China's urbanization in the future, there is still vast potential for urban development. China will form an urbanization pattern with urban agglomerations as the mainstay and diversified development of large, medium and small cities and towns. The urban pattern of spatial diffusion will create more development opportunities.

China is responsible for a quarter of the world's carbon emissions, thus undertaking huge obligations for emission reduction. In order to fulfill the responsibilities as a major power, China submitted to the United Nations *"Strengthening Climate Change Action: China's Nationally Determined Contribution"* on June 30, 2015, which stated that: China will aim to peak CO_2 emissions around 2030 and strive to reach an early peak; total CO_2 emissions per unit of GDP should be down by 60–65% from the level in 2005; non-fossil energy as a percentage of primary energy consumption should reach about 20%. To materialize the goals, the State Council formulated and issued the *"Work Plan for the Control of Greenhouse Gas Emissions during the 13th Five-Year Plan Period"* in October 2016, in which clear targes were set: by 2020, CO_2 emissions per unit of GDP will drop by 18 compared to 2015 with total carbon emissions under effective control; support priority development areas to reach the peak ahead of others, and strive to peak emissions in some heavy chemical industries around 2020, with fruitful progress in low-carbon transformation of the energy system, industrial system and the consumer sector; the national carbon emissions trading market should be launched, a framework of laws, regulations and standards should emerge to tackle climate change, and a system of statistical accounting, evaluation and accountability systems should be improved; low-carbon pilots and demonstrations should be scaled up, with enhanced synergy between pollution reduction and emission cut, and growing public awareness of low carbon development. These commitments represent the milestones that China has set in terms of total emissions, energy mix, low carbon pilots, etc in order to made steady headway towrds an early peak.

By the analysis above, China will see rising urbanization as well as total carbon emissions in the future, but at a slower pace. The time when China is expected to hit the peak (around 2030) is close to when the country reaches a high level of urbanization (2035), suggesting that China's urbanization and CO_2 emission reduction not only exhibit historical linkage, but also future connections.

For all the progress China has made in improving its eco-environment, there is still a long way to go to achieve low-carbon and sustainable development amid rapid urbanization. How on earth does urbanization impact carbon emissions? Are there

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[3] In December 2019, Economic Institute of CASS and Social Sciences Academic Press jointly unveiled *the Economic Blue Paper: China's Economic Growth Report (2018–2019).*

regional disparities for this impact? What should be the proper size and distribution of future Chinese cities? Answers to these questions will be of great help in driving scientific urbanization, energy conservation and emission reduction in the country.

2.3 Impact Mechanism of China's Urbanization on Carbon Emissions and Empirical Analysis

2.3.1 Analysis Framework Based on STIRPAT Model

The factors driving the growth of carbon dioxide emissions include economic development, industrial structure, technological progress, energy consumption, total population, people's life, cultural mindset, etc, which are constantly shaped and changed in the process of urbanization. Therefore, it is a challenging systematic project to study the mechanism of urbanization on carbon emission. Ehrlich & Holdren (1971) first put forward the famous IPAT model, which explored the effect of human activities on the natural environment from the three main dimensions of population, affluence and technology. Subsequently, Dietz & Rosa (1997) modified the IPAT model, and took into account the Stochastic Impact of population growth, wealth change and technological progress on the environment, and proposed the STIRPAT model:

$$\mathrm{I_{it}} = \mathrm{aP_{it}^{b}A_{it}^{c}T_{it}^{d}}\varepsilon_{\mathrm{it}}$$

The logarithmic form is:

$$\ln \mathrm{I_{it}} = \mathrm{a} + \mathrm{b}(\ln \mathrm{P_{it}}) + \mathrm{c}(\ln \mathrm{A_{it}}) + \mathrm{d}(\ln \mathrm{T_{it}}) + \varepsilon_{\mathrm{it}}$$

Among them, variables P, A and T have the same meaning as before, and I represents the impact of the environment, usually expressed by carbon dioxide or other environmental indicators; a represents the fixed constant term, while b, c and d represent the elastic coefficients of the three variables, which are all undetermined parameters. In addition, i stands for the observed individual, t is the observed year, and ε is the error term.

The study of York et al. (2003) found that socio-economic factors or other control factors can join into the STIRPAT model, assuming these are conceptually consistent with the multiple settings of the model. As a result, STIRPAT is widely used in environmental and economic research due to its adaptability and inclusiveness. For instance, Wang and Liancheng (2015) used the fixed assets stock per capita and the added value per capita in manufacturing as proxy variables of population and wealth in STIRPAT, and analyzed the correlation between the growth of China's manufacturing output and the level of energy consumption and carbon dioxide emissions. Taking OECD countries as an example, Emrah & Ulucak (2019) incorporated energy R&D expenditure into the technical dimension of STIRPAT model, and explored the dynamic relationship between energy technology improvement and carbon emissions. It can be found that the literature on different topics has enriched and expanded the STIRPAT model to different degrees in combination with its research needs. In light of the main features in China's urbanization process, the paper establishes the following STIRPAT model:

$$\begin{aligned}\ln \mathrm{CO}_{2\mathrm{it}} = \mathrm{a} + \beta_1 \ln \mathrm{CO}_{2\mathrm{it}-1} + \beta_2 \ln \mathrm{P}_{\mathrm{it}} + \beta_3 \ln \mathrm{PGDP}_{\mathrm{it}} + \beta_4 (\ln \mathrm{PGDP}_{\mathrm{it}})^2 \\ + \beta_5 \ln \mathrm{SI}_{\mathrm{it}} + \ln \mathrm{TI}_{\mathrm{it}} + \beta_7 \ln \mathrm{FDI}_{\mathrm{it}} + \beta_8 \ln \mathrm{EI}_{\mathrm{it}} + \varepsilon_{\mathrm{it}}\end{aligned}$$

Among them, CO_2 stands for urban carbon dioxide emissions. The core explanatory variable is the urban population P, which represents city size. The control variables include urban per capita GDP (PGDP), the proportion of urban secondary industry output in GDP (SI), the proportion of urban tertiary industry output in GDP (TI), the foreign direct investments in cities (FDI), and urban energy intensity (EI). a is the constant term, $\beta_1 - \beta_8$ are the undetermined parameters, and ε is the error term. In addition, city carbon dioxide emission is lagged by one order to explore the lagging effect of urban carbon emission. To test whether the Environmental Kuznets Curve hypothesis is valid in Chinese cities, the square term of GDP per capita was added.

Due to the lack of data for energy consumption structure of Chinese cities, it is difficult to accurately measure urban carbon emissions. We use the following estimation methods: First, calculate the total energy consumption (tons of standard coal) of prefecture-level cities based on energy consumption intensity, growth in energy consumption per unit of GDP in the statistical yearbooks of some provinces and prefecture-level cities. Second, according to the value recommended by the National Development and Reform Commission Energy Institute, the burning of 1 kg of standard coal releases 0.67 kg of carbon (the reference value of the Japan Institute of Energy Economics is 0.68 kg, and that of the US Department of Energy's Energy Information Administration is 0.69 kg). And based on the chemical combustion formula of carbon, burning 1 kg of carbon in oxygen produces about 3.67 kg of carbon dioxide. Through the conversion of these values, burning 1 kg of standard coal would emit 2.46 kg of carbon dioxide, thus the total amount of carbon dioxide emitted by various cities could be calculated.

This paper selects 144 prefecture-level cities in China from 2007 to 2018, including 56 cities in east China, 55 cities in central China, and 33 cities in west China. The samples range from small cities with a population of 126,300 and megacities with a population of 25,205,200, both with sufficient samples. The lage sample range is conducive to expanding the interpretation of estimated results. The data of total energy consumption and energy consumption per unit of GDP of various cities is derived from local statistical yearbooks; urban population data comes from "China Urban Development Statistical Yearbook"; data of urban per capita GDP, output of secondary industry as a percentage of GDP, output of tertiary industry as a percentage of GDP and FDI come from "China Urban Statistical Yearbook" and the statistical announcements of national economic and social development of prefecture level cities.

2.3.2 Impact Mechanism of China's Urbanization on Carbon Emissions and Empirical Analysis

2.3.2.1 Urban Population Size and CO_2 Emissions

The expansion of urban population is an inevitable result of urbanization, with a direct bearing on regional carbon dioxide emissions. Figure 2.7 shows that there is a positive correlation between urban population and total carbon dioxide emissions. The increase of urban dwellers will induce great changes in local lifestyle, industrial structure, living environment, transportation and other aspects, and energy consumption would soar, in contrast to that in rural areas. Cities thus become the center of regional carbon emission, holding the key to curbing greenhouse gas emission in China.

On the other hand, the increase of the urban population is not entirely negative for greenhouse gas emissions. Figure 2.8 revels that as urban population rises, per capita carbon dioxide emissions are falling as a whole. This means the scale effect of cities is somewhat helpful for curbing carbon emissions, as large cities are conducive to joint construction infrastructure, connectivity of information and sharing of production factors. Specifically, the impact of urban population on per capita carbon emissions

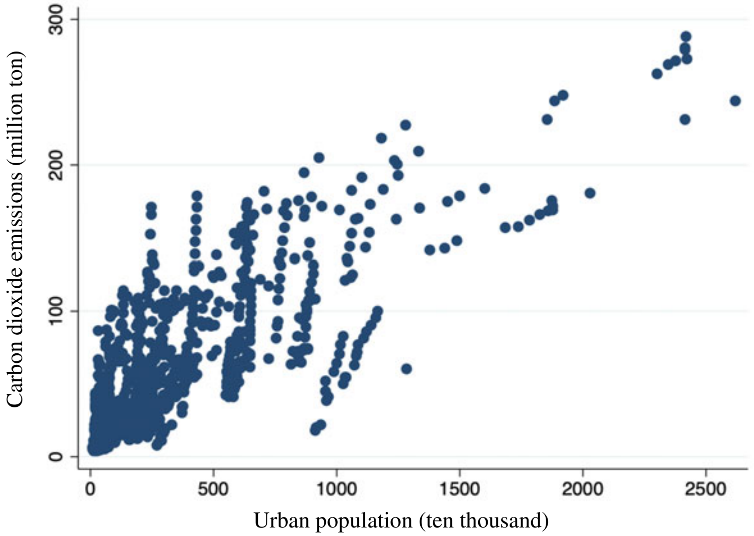

Fig. 2.7 Scatter diagram of China's urban population size and carbon emissions

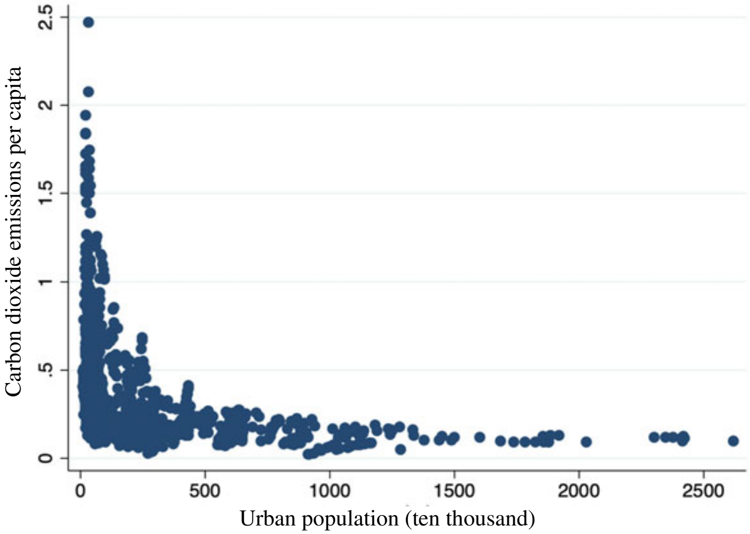

Fig. 2.8 Scatter diagram of China's urban population size and carbon emissions

can be defined in two different scenarios: when population is below 5 million, the per capita carbon emissions drop sharply with the increase of population, indicating the role of city scale effect; if the urban population exceeds 10 million, the per capita carbon emission has not been significantly curbed with the increase of population. Therefore, a city is not conducive to reducing per capita carbon emissions if it's too small or too large.

Based on the box chart (Fig. 2.9) of urban population size in China, its east, central and western regions, one may find that: first, the median population size of the sample cities is 760,000, suggesting that medium-sized cities are the mainstay in China. Secondly, there are many outliers in China's urban population size, as is shown in the first sub-graph, where quite a few cities have over five million population. Thirdly, great disparities exist between population in eastern cities and that in central and western cities, with the median figure of the former being 2.3 million, and the latter, around 600,000. Fourth, the eastern region sees a relatively evenly distributed cities with different population sizes that cross a wide spectrum, and only cities with population over 14 million are classified as outliers. In general, China's urban population is relatively concentrated, with great regional disparities, and has a certain number of central megacities.

To explore the impact mechanism of urban population size on carbon emission, a panel fixed effect estimation of the STIRPAT model was conducted. The estimated results (ln P row in Table 2.1) show that, at the national level, the impact of urban population size on carbon dioxide emissions is significant. For each 1% increase in urban population, carbon dioxide emissions grow by 0.196%. At the regional level, the impact of population size on carbon emissions in eastern cities is slightly

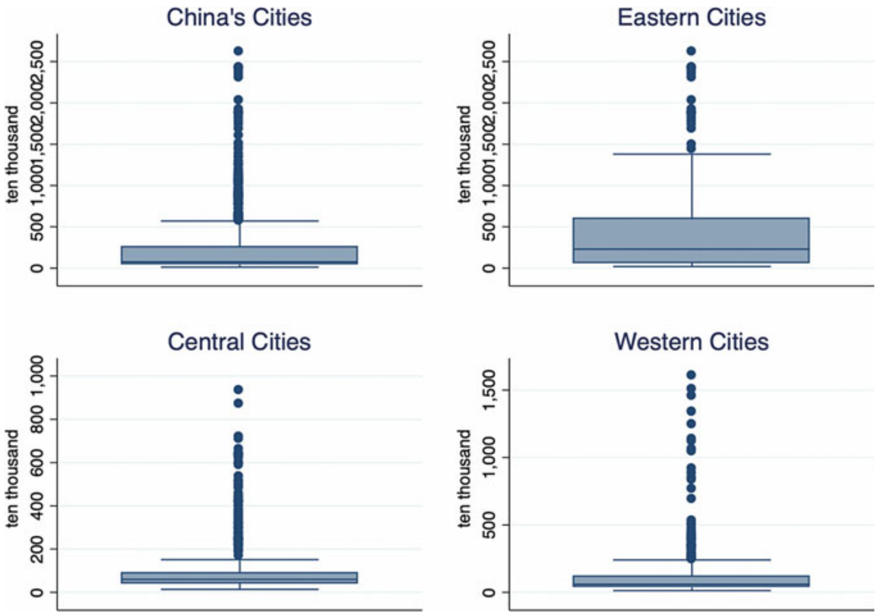

Fig. 2.9 Distribution of urban population size in china and its different regions

higher than that in central cities. The question of whether larger urban population will lead to higher marginal carbon emissions is subject to further debate. Secondly, the population size of western cities has the smallest and insignificant impact on carbon emissions, though its distribution is relatively similar with that of central cities. It could be said that regional differences exist in terms of the impact of urban population size on carbon emissions due to different geographical environments, cultural mindsets, etc.

2.3.2.2 Urban Per Capita GDP and Carbon Dioxide Emissions

Urbanization is marked by improved human material production, which is seen in the increase of per capita wealth. Economic interest is the primary driver of population migration, changes of land type, and industrial structural transition. The relationship between urban per capita GDP and carbon dioxide emission is essentially the one between economic growth and environmental protection. The Environmental Kuznets Curve (EKC) says that in case of a poor country or region, the increase of per capita income would lead to rising environmental pollution; and in case its economic growth reaches a certain critical point, the further increase of per capita income would be accompanied by declining environmental pollution, with improved environmental quality, exhibiting a distinct inverted U-shape. Yet this curve theory has not been unanimously agreed by the academic community, as other theories have

Table 2.1 Estimated result of fixed effect model

	Model 1	Model 2	Model 3	Model 4
	China's cities	Eastern cities	Central cities	Western cities
VARIABLES	ln CO_2	ln CO_2	ln CO_2	ln CO_2
d. ln CO_2	0.313***	0.158*	0.0704*	0.417***
	(0.0433)	(0.0806)	(0.0396)	(0.0276)
lnP	0.196***	0.246***	0.229***	0.103
	(0.0455)	(0.0675)	(0.0775)	(0.0696)
lnPGDP	−1.068***	2.702***	−0.940***	−1.461***
	(0.273)	(0.632)	(0.348)	(0.161)
(lnPGDP)^2.	0.0829***	-0.0946***	0.0850***	0.105***
	(0.0150)	(0.0286)	(0.0163)	(0.0118)
lnSI	0.168*	0.0753	0.0660	000,997
	(0.0914)	(0.271)	(0.0537)	(0.223)
lnTI	0.0882	0.516**	−0.0199	−0.200
	(0.0919)	(0.247)	(0.0674)	(0.180)
lnFDI	−0.0333***	−0.0124	−0.00164	−0.0158
	(0.00987)	(0.0157)	(0.0132)	(0.0132)
lnEI	0.611***	0.603***	0.825***	0.571***
	(0.0645)	(0.114)	(0.0506)	(0.0782)
Constant	−0.400	−21.73***	−3.049	3.549**
	(1.387)	(2.931)	(2.116)	(1.608)
Observations	1,584	616	605	363
R-squared	0.690	0.833	0.789	0.681
Number of id1	144	56	55	33

* represents significant level

***, **, * indicate significant at the level of 1%, 5%, and 10% respectively

found that the relationship between economic growth and environmental pollution is characterized by U-shape, N-shape, monotonously rising, or monotonously falling pattern, which challenges the validity of EKC hypothesis. For China's urbanization, how does urban per capita GDP correlate with carbon dioxide emissions? Does the correlation show any regional characteristics? Answers to these questions help one understand the impact mechanism of urbanization on carbon emissions.

The per capita GDP (mean value during period of observation) of China's 144 prefecture-level cities was 461.1342 million yuan. Per capita GDP of the eastern cities stood at 622.2829 million yuan, much higher than that of the central and western cities, indicating the lead in economic development of the eastern cities over their central and western counterparts. In addition, the standard deviation of per capita GDP in eastern cities was registered at 43,455.07, the largest among the

Table 2.2 Urban per capita GDP by region (unit is ten thousand yuan)

	Mean	Standard deviation	Frequency
Western cities	33227.29	19562.22	33
Central cities	37437.24	25120.16	55
Eastern cities	62228.29	43455.07	56
Total	46113.42	35069.87	144

three regions, which signifies greater gap between the rich and the poor in the eastern region despite its high per capita income (Table 2.2).

To explore the quantitative impact of per capita urban GDP on carbon emissions in China's urbanization process, an estimate of panel fixed effects was conducted based on STIRPAT model. The result (lnPGDP and $(\ln \mathrm{PGDP})^2$ in Table 2.1) shows the EKC hypothesis, i.e. the inverted U-shaped relationship between income level and environmental pollution, is not valid for the sample Chinese cities, because the quadratic estimated coefficient of per capita GDP is positive (0.0829). This might result from the differences in the development model and energy mix of different Chinese cities. Some emerging cities might have stayed away from the traditional path of "pollution first, treatment later", which is beyond the explanation of the ideal Environment Kuznets Curve for its structural complexity and diversity. Empirical analysis at the regional level is more interesting: EKC hypothesis holds in the case of eastern cities, but not in the case of central and western cities. In some measure, this illustrates the late start of central and western cities in their development, and the lessons learned from their eastern peers regarding urbanization: i.e: the conscious policy and communication efforts to forestall excessive growth of carbon emissions when developing urban economy. This proves that with the implementation of the notion of low-carbon cities and citizens' heightened environmental awareness, China's emerging cities have striked the balance between economic development and environmental protection.

2.3.2.3 Urban Industrial Structure and CO_2 Emissions

Industrial structure mirrors the economic level and development model of a city, exerting great impact on regional greenhouse gas emissions. As developed countries are highly urbanized and industrialized, their industrial structure tends to be stable, with two-thirds of carbon emissions from the consumer sector. In this connection, low carbonization of the consumer sector (especially the way of urban living) is high on the agenda for building low-carbon cities in the developed world. On the contrary, China's urbanization is growing rapidly, with continuously rising percentage of the secondary and tertiary industries in GDP. Impacts on cities' total energy use, energy consumption mix and energy consumption intensity differ for different industrial structures. And extensive and inefficient industrial structure and development model will inevitably incur rising greenhouse gas emissions. In developing low-carbon economy and building low-carbon cities, it's essential to gain deeper insight into the current development and trend of urban industrial structure, and define the impact mechanism of different regional industrial structures on carbon emissions.

According to the trend chart of changes in the industrial structure of Chinese cities from 2007 to 2018 (Fig. 2.10), over the 12 years, the size of the secondary industry as a percentage of GDP expanded before it registered a fall; and that of the tertiary industry dropped before it recovered, and the two were coming closer as a result. In 2018, the share of secondary industry was slightly higher than that of the tiertiary, which testified to the upgrading urban industrial structure in China. Nevertheless, as service sector represents over 70% of GDP in the developed world, tertiary industry in China still promises great potential for growth. At the regional level, the share of the secondary industry in GDP witnessed a steady fall in eastern cities during the same period; and for the first time in 2010, the contribution of secondary industry to GDP in western cities overtook that in the east, and has long maintained the lead over its eastern and central peers thereafter, despite its overall decline in western cities during this period. Secondly, the contribution of tertiary industry to GDP in eastern cities has been greater than that in central and western cities over a long time, and the proportion of the industry in central cities is fairly close to that in the west. It's evident that the overall urban industrial structure is undergoing continuous upgrading across regions in China, but not without distinctive regional differences. To be specific, central and western cities trail behind their eastern counterparts in the upgrading of industrial structure due to the first mover advantage of the east in embracing reform and opening up, hence its lead in industrial upgrading with state-of-the-art hardware and software, which conforms to the basic law of industrial development.

To understand how periodical characteristics and regional differences of urban industrial structure affect regional carbon dioxide emissions during urbanization in China, an estimate of panel fixed effects was conducted based on STIRPAT. The

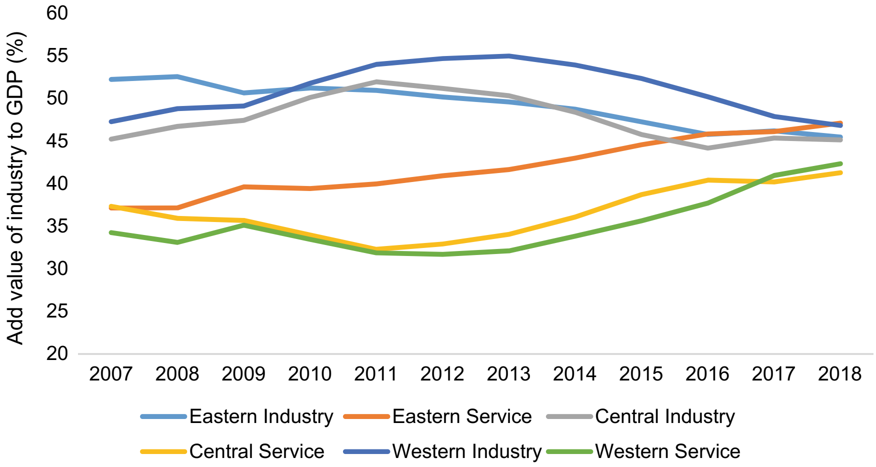

Fig. 2.10 The change trend of industry change in China's cities from 2007 to 2018 *Data source* National bureau of statistics

empirical results illustrated that (ln SI and ln TI in Table 2.1) across the country, secondary industry exerts major impact on carbon dioxide emissions. Every 1% increase in the share of the secondary industry in GDP is accompanied by 0.1168% rise in carbon dioxide emissions. Cities' service industry bears small and insignificant impact on carbon dioxide emissions, implying less carbon footprint and smaller environmental externality of the service industry. At the regional level, no major impact was found from the service industry on carbon emissions of central and western cities, pointing to the contribution of a growing tertiary industry to building low-carbon cities there. However, the servie industry exerts considerable positive impact on carbon emissions in eastern cities (0.516). This seemingly counterintuitive empirical result could, in some measure, explain the following realities: the size of cities in the east tends to be bigger than that in central and western China, calling for tremendous amount of services to support urban life and work. Recent years have witnessed accelerated industrial upgrading, with a great many heavy industries in eastern cities relocated to central and western regions. The thing is, the service industry is not entirely "pollution-free". It also involves transportation emissions, high energy consumption and dirty processes. The inherent low-carbon strength of the service industry would not be maximized without proper planning and guidance to enhance its internal structure and quality.

2.3.2.4 FDI in Cities and CO_2 Emissions

The impact of urbanization is not confined to the change of the industrial structure within the region. It opened up the relatively closed local economy, dramatically increasing the external dependence of the economy. Foreign direct investments are utilized for factory building, mass production, product processing and export, creating economic gains for cities. However, while benefiting from the relocation of industrial capacity from the developed world, cities have also tasted the bitter fruit of surging carbon emissions. The scale effect of urbanization may turn out to provide "shelters" for pollution in Chinese cities. But in all fairness, the environmental effects of FDI on Chinese cities are not all negative. Studies have found that FDI may help phase out backward urban production capacity in developing countries, propelling transformation of urban industrial structure and enhancement of local production technologies and energy efficiency through technology spillover, triggering structural and technological upgrading, thus curbing greenhouse gas emissions in developing countries. So here comes the question: amid growing urbanization in China, what impact on earth does FDI bring to China in terms of urban carbon emissions, positive or negative? And how does it affect carbon dioxide emissions across cities and regions in China?

An analysis of the FDI amount in Chinese prefecture-level cities from 2007 to 2018 was conducted to define its trend in these cities across regions in China, as shown in Fig. 2.11. Statistics reveal that in the past 12 years, FDI has been on the rise across prefecture-level cities of all regions in China, but with significant regional differences in this regard, which can be found in its decreasing amount from the east

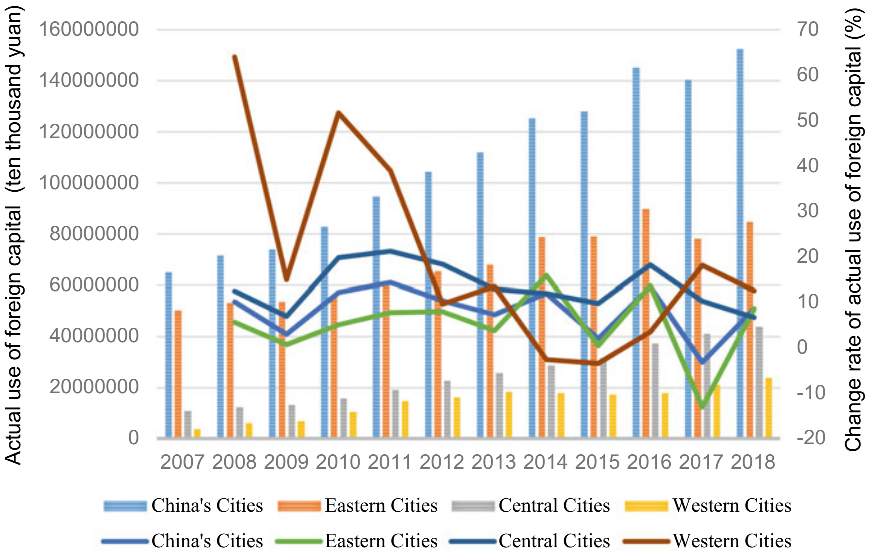

Fig. 2.11 Actual use of foreign capital from 2007 to 2018 *Data source* National Bureau of Statistics

to the west. In terms of the potential of FDI attraction, central cities have continued to see higher growth than their eastern peers, despite their lower amount of FDI, pointing to the increasing attractiveness of central Chinese cities with their cheap labor costs and strong industrial base, etc, and promising more relocation of industrial capacity to the region from eastern China and abroad. From the stability point of view, more fluctuations in FDI were detected in western cities, indicating smaller size of FDI and greater uncertainties in this region, which is subject to more influence from local industrial policies, infrastructure, and labor force structure, among others. On the whole, from 2009 to 2011, as international production activities steadily recovered in the wake of the global financial crisis, substantially larger FDI had been poured into Chinese cities. After 2012, however, the share of FDI in the investments of Chinese cities fluctuated in a modest downward range.

Given the current development and characteristics of FDI in China's prefecture-level cities, an empirical approach was adopted to explore the impact of FDI in China and other regional cities on greenhouse gas emissions. The research (the row of lnFDI in Table 2.1) found that, FDI in cities exerts tremendous impact on carbon emissions across the country. Every 1% increase in FDI in cities would help reduce urban carbon dioxide emissions by 0.033%. At the regional level, no apparent regional differences were detected in terms of the impact of cities' FDI on carbon emissions. This conclusion does not mean that foreign investors have not transferred pollution during accelerating urbanization in China. It's just that with its structural effect and technological progress, FDI could curb greenhouse gas emissions to some extent.

2.3.2.5 Urban Energy Intensity and CO_2 Emissions

Energy intensity refers to the energy use per unit of GDP, which is generally measured as tons of standard coal per 10,000 yuan. It serves as an effective tool to identify the energy efficiency and the level of energy technology of a city. Lower energy intensity equates to lower carbon emission per unit of GDP, which, in some measure, helps contain the growth of urban carbon emissions. Therefore, a reduction in urban energy intensity has become a consensus among local governments in China, which has been incorporated in their annual work plans or summary reports. Energy intensity can be grouped into three categories by sector: energy intensity of the production sector, energy consumption per unit length of transportation lines and residential energy intensity. In theory, the decline of energy intensity in a certain sector suggests its improved energy efficiency. With other factors remaining unchanged, the CO_2 emissions from energy use in the sector are bound to decrease, which means lowering energy intensity would create negative contribution to CO_2 emissions growth. On the contrary, increasing energy intensity would positively contribute to pushing up CO_2 emissions. It's clear that energy intensity involves many aspects of urban life and work, and its impact on carbon emissions is the result of multiple factors.

Analysis of changes in energy intensity in China's prefecture-level cities from 2007 to 2018 suggested a general decline in energy intensity across cities and regions in China, and a greater drop was detected in central and western regions than in the east, as shown in Fig. 2.12. In 2007, there was a wide gap of energy intensity between eastern cities and cities in central and western China. After 2016, the gap has been dramatically narrowed. This reminds us that energy intensity reduction and urbanization growth are not at odds. Since urbanization leads to scale-effects of agglomeration, the reduction of energy use per unit of GDP would surely become the norm as urbanization grows. But the question of whether this agglomeration would

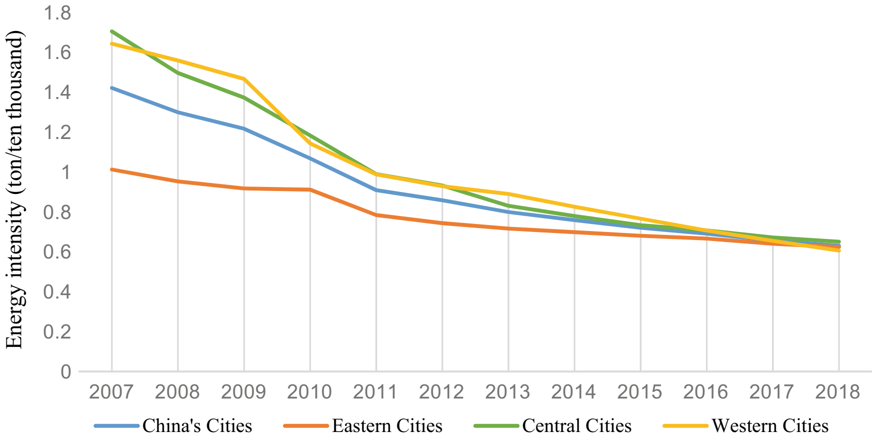

Fig. 2.12 The trend of energy intensity from 2007 to 2018 *Data source* National bureau of statistics

negatively affect energy intensity due to over-saturation of cities is subject to further debate.

The empirical results (the row of lnEI in Table 2.1) revealed major impact of urban energy intensity on carbon dioxide emissions, which is larger than that of urban population, industrial structure, foreign investment, etc. For every 1% reduction in urban energy intensity across the country, carbon dioxide emissions would go down by 0.611%, meaning that energy intensity is of crucial significance to regional carbon emissions. The priority of cutting urban greenhouse gas emissions in China lies in reducing energy intensity and improving energy efficiency. In addition, greater impact of energy intensity on carbon emissions was found in central cities than in their eastern and western counterparts. This might be explained by the role of central cities as the recipient of industrial transfer from eastern China and abroad as well as the rising share of secondary industry in local GDP with industrial restructuring. In the future, central cities need to reduce the weight of heavy industries in the economy, curtail high-intensity demand of the heavy chemical industry for fossil energy, promote the application of energy-saving and emission-reduction technologies, and enhance efficiency of energy utilization.

2.4 Conclusions and Policy Recommendations for Low-Carbon Development During China's Urbanization

Urbanization in China has been characterized by rising carbon emissions, huge energy consumption and greater eco-environment pressure than that of developed world, and has been troubled by the lock-in effect of vast industrial production capacity and infrastructure, among other low-carbon challenges. This chapter begins with a diagnosis of the historical interactions between China's urbanization and carbon emissions, and proceeds to explore the impact mechanism of urbanization on carbon emissions. Finally, the panel data of 144 cities from 2007 to 2018 are taken as samples for assessing the regional differences of the impact and how the impact is enforced. Research findings are listed below:

(1) At the national level, the evolution of both carbon emissions and urbanization can be divided into three stages, with the two sharing the same trajectory of changes. Growth in urbanization has been accompanied by rising carbon emissions. From the regional standpoint, China's urbanization presents a multi-level pattern, higher in the eastern region and lower in the west, and the distribution of average carbon emissions depicts a similar tier. China's projected peak in carbon emissions (around 2030) coincides with high levels of urbanization (2035), suggesting a strong correlation between China's urbanization and carbon dioxide emissions, not only in the past, but also in the future.

(2) The impact of urbanization on carbon emission involves a variety of factors, depending on population size, per capita GDP, industrial structure, energy intensity and FDI, among which the size of population has a direct bearing on carbon emissions, while per capita GDP, industrial structure, energy intensity and FDI bring indirect impacts on carbon emissions. In this process, regional disparities come in to affect the way and size of the impact on carbon emissions. Only with a holistic examination of all factors at play can we accurately define the final impact.

(3) At the national level, the urban secondary industry exerts major impact on carbon dioxide emissions. In contrast, the impact from the tertiary industry is small and insignificant, indicating a lower carbon footprint and smaller environmental externality in the sector. FDI in cities brings considerable impact, but smaller compared with other factors. The factor of urban energy intensity also comes into play, greater than all other variables.

(4) At the reginal level, the tertiary industry bears great positive impact on the carbon emissions in eastern cities, but no significant impact is found in central and western cities, meaning that the central and western cities, predominated by the secondary industry, are still going through industrial upgrading. The large tertiary industry in eastern cities makes for higher cost for carbon emission compared to other regions when the share of the industry grows. Urban energy intensity brings dramatic impact on carbon dioxide emissions, with greater impact in central China than in the east and west. FDI serves as a slight inhibitor for urban carbon emissions across the eastern, central and western regions.

Building on the research findings, the following policy recommendations are made:

(1) A balanced viewpoint should be adopted towards the current challenges in low-carbon development. Urbanization goes hand in hand with fast economic growth and rising energy demand. At the same time, China is obliged to curb carbon dioxide emissions. This calls for a balance when developing the economy. China's urbanization will not slow down, but opportunites can still be found for energy conservation and emission reduction. By recognizing challenges for low-carbon development, encouraging low-carbon footprint in the future life and work in cities, China will make more contribution to the development of low-carbon industries across the world.

(2) The eastern region should prioritize low-carbon development of its tertiary industry due to its great impact on carbon emissions in the region. In the future, while increasing the weight of the tertiary industry, Chinese policy makers should also seek to enhance the internal structure of the industry. The acceleration of China's economic restructuring and industrial transformation will put the service industry in a stronger position in the economy, which will inevitably push up its carbon emissions from energy use. But the service industry is not entirely free from pollution, as the sector comprises both production services and residential services, the former having greater potential for emission reduction. High-end services such as cultural creativity, financial services, R&D, design

and e-commerce should be encouraged. The percentage of transportation and real estate within the tertiary industry should be adjusted downward to reduce carbon emissions.

(3) Spur technological innovation in energy conservation and emission reduction to curtail energy intensity, which brings tremendous impact on carbon dioxide emissions. It's essential to drive innovation in energy-saving technologies and reduce energy intensity, especially in the production sector. Some technologies of the production sector remain in the concept stage, and will take some time for their practical applications. This brings the need to ramp up research on the integration of multiple energy sources in the energy system with heavier R&D investments in key technologies. Capitalize on the research resources and strength of environmental protection agencies, research institutes and universities to encourage private investments in new technologies. Central China sees the highest energy intensity among the three regions, which might be attributed to the industrial transfer, especially the transfer of heavy and chemical industries to the central cities from the east. Therefore, energy conservation and emission reduction efforts in the central region should focus on the secondary industry, cutting the direct carbon emissions of energy-intensive sectors by phasing out backward production capacity, optimizing energy consumption mix and developing environmental protection industries.

(4) Open up wider to the outside world to attract more foreign investments. It has been found that existing foreign investment projects have failed to produce major impact on carbon emissions reduction. In the future, China is advised to encourage FDI projects to match its urbanization needs on reasonable conditions of environmental protection. In recent years, Chinese authorities have promulgated *Notice on Measures to Expand Opening-up and Actively Use Foreign Capital, Notice on Measures to Promote Foreign Investment, and Notice on the Positive and Effective Use of Foreign Capital for High Quality Economic Development*, which mainly aim to substantially open up service sectors, fully liberalize general manufacturing industry, ease or remove the cap on foreign holdings in companies in some areas, loosen or cancel restrictions of business scope, vigorously promote investment facilitation, put domestic and foreign companies on a level playing field, propel innovation at national development zones, strengthen utilization of foreign capital, allow local governments to formulate incentives to attract investment within statutory limits of their authority. Leverage data, the new production factor, to create an efficient and convenient foreign investment supervision framework in the future, enhance connectivity of the information management systems of the Ministry of Commerce, industrial authorities, Ministry of Finance, customs administrations, foreign exchange administrations, tax bureaus, etc, thereby ensuring cross-departmental sharing of information regarding foreign-invested enterprises from their establishment to operation.

(5) Change the mindset of urban planning to accommodate the concept of smart cities. Upgrade the industrial structure of core cities without changing the central position of urban agglomerations. This would strengthen the cost advantage of

small cities and towns and ease their geographical weakness. Ensure coordinated development of large, medium and small cities and towns, which could co-build and share infrastructures, and benefit from the transfer of functions and industrial capacity from megacities, creating mutual benefits and win-win outcome. Smat cities can enable a robust response system for smart public service and urban management. Aided by information technology, professional application systems could be strengthened, including employment, health care, culture, and housing among others, to promote urban data integration, cross-departmental information sharing, interactions among industries and accurate management of urban operation, etc. Through activating dynamic city-wide response to incidents and various disasters, future cities would be better positioned to prevent, prepare for, respond to, and recover from disasters – the testament to meaningful and stronger smart cities.

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Chapter 3
Low-Carbon Transition (Peaking) of Chinese Cities: The Case of Beijing

Jian Zhou and Shiyan Chang

Abstract The low-carbon transition (peaking) initiatives of Chinese cities will aim at meeting SDG and climate change requirements. These cities set their unique targets and paths for low-carbon transition (peaking) based on their own energy mix, industrial structure and renewable energy endowment. Taking Beijing as an example, this chapter analyses the trend of energy consumption and CO_2 emission under varied policy measures and puts forward corresponding policy recommendations.

Keywords Low-carbon cities · Low-carbon transition · Peaking · Beijing

3.1 Analysis on Emission Peaking Target of Major Chinese Cities in the Context of SDG and Climate Change[1]

3.1.1 SDG's Carbon Emission Targets at the City Level

Cities serve as the gateway for ideas, commerce, culture, science, productivity and social development. At their best, cities uplift people socially and economically. But challenges are commonplace: congestion, lack of funds to deliver basic services, housing shortages and declining infrastructure. The current development and challenges are as follows: half of the world's population, about 3.5 billion people, now live in cities; by 2030, nearly 60% of the world's population, or some 5 billion people, will be urban dwellers; around 95% of urban expansion in the coming decades will take place in developing countries; 828 million people now live in slums, and the

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number is rising; cities in the world cover only 3% of the earth's land, yet consume 60–80% of its energy and produce 75% of its carbon emissions. Surging urbanization puts a strain on freshwater supplies, sewage treatment, living environment, and public health; but high-density cities can bring efficiency gains and technological innovation, while cutting resource and energy use.

These challenges can be tackled by growing prosperity and development, increasing the use of resources and reducing pollution and poverty. The future that people envisons will include cities that provide opportunities for all and enable access to basic services, energy, housing, transportation and more for all.

The Sustainable Development Goals (SDGs) of the United Nations aim to address development issues, once for all, in the social, economic and environmental dimensions in an integrated approach from 2015 to 2030, and move towards sustainable development. The SDGs relevant to cities are sustainable cities and communities—make cities and human settlements inclusive, safe, resilient and sustainable. Specific targets include:

(1) By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.
(2) By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.
(3) By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.
(4) Strengthen efforts to protect and safeguard the world's cultural and natural heritage.
(5) By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.
(6) By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
(7) By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.
(8) Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning.
(9) By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the *Sendai Framework for*

Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels.

(10) Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials.

3.1.2 Peaking or Control of Carbon Emissions at the City Level Under Global Climate Change Governance

Global climate change governance is rapidly diversifying. The 2015 Paris Agreement adopted a bottom-up framework for global climate governance, which institutionalized the participation of non-state and sub-state actors in global climate governance (UNEP 2016). The UNFCCC process has been accompanied by national and regional initiatives to promote participation of non-state and sub-state actors in global climate governance in the European Union, Latin America and Asia, among others.

3.1.2.1 The Sub-State Levels of Government: City, State and Region

There are networks linking cities, states and regions to act on climate change. Figure 3.1 shows the number of non-state and sub-state actors and their geographical distribution in some networks, including the Global Covenant of Mayors for Climate and Energy signed by 9149 cities that represent 780.8 million people, or over 10% of the global population. All these members are committed to submitting separate Sustainable Energy and Climate Action Plans, or to cutting CO_2 emissions by 40%

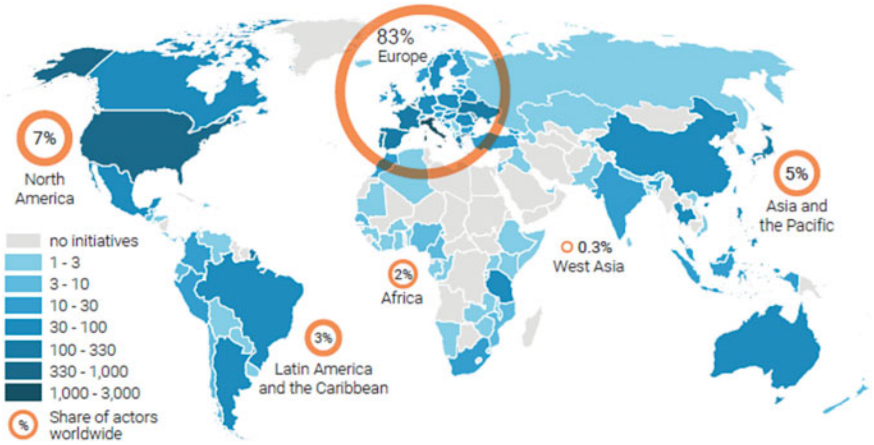

Fig. 3.1 Regional distribution of non-state and sub-state actors in major urban networks. *Source* UNEP. Emissions Gap Report 2018

Table 3.1 Growth of participation of non-state and sub-state actors from 2015 to 2017

	2015	2017
Cities	7025 from 99 countries/regions, accounting for 11% of the global population	7378 from 133 countries/regions, accounting for 16.9% of the global population
State and regions	116 regions from 20 countries/regions, accounting for 11% of the global population	245 regions from 42 countries/regions, accounting for 17.5% of the global population

by 2030. ICLEI, a global network of subnational governments, has developed the Carbon Climate Registry, which covers more than 1000 towns and regions from 89 countries, representing 9% of the world's population.

Coordinating state and regional government actions, the State and Region Compact (2017) consists of 110 regional governments from 36 countries, representing 658 million people, representing about 18% of the world economy, with a baseline emission of 3.9 gigatonnes of CO_2 equivalent. These governments have committed to 290 climate actions, focusing on emissions reduction, renewable energy use and energy efficiency. If the climate targets are met on time, these actions are expected to deliver a total of 21.9 $GtCO_2e$ reduction between 2010 and 2050 (Table 3.1).

3.1.2.2 International Cooperation Initiatives (ICIs)

The International Cooperation Initiative (ICIs), by drawing in large and growing Numbers of non-state and sub-state actors, can deliver considerable emissions reductions, but only if they meet the stated goals and do not displace actions elsewhere. The Climate Initiative Platform is currently tracking 244 initiatives, of which 220 center on mitigation. Since the launch of 2016 UN Emissions Gap Report, the platform has added 17 new initiatives.

(1) Regional and Sectoral Involvement
As Fig. 3.2 shows, many programs are implemented in multiple locations. Regional participation in ICIs has grown in almost every region despite the modest growth of the mitigation-based ICIs tracked since 2016. The largest increase was recorded in Latin America and the Caribbean, where the number of registered information systems climbed from six in 2016 to 25 in 2018. Participation of Western Europe, Asia and the Pacific roughly doubled from that in 2016. In addition, ICIs activities were concentrated in high-and-middle-income countries, and ICIs operating in low-income countries or regions also saw notable growth by 56% between 2015 and 2017, and 50% increase was found in low-and-middle-income countries during the same period. Despite these advances, the north–south gap remains glaring.

(2) Area of Focus

Majority of the ICIs cover multiple fields, mostly focusing on key areas where potential for mitigation is much higher than the emission reduction implied in current policies and the NDC. The sectoral focus of ICIs varies depending on the needs and capacities of the regions where they are implemented. Actions targeting disaster resilience and agriculture most frequently took place in low-and-middle-income economies, while actions in the industrial sector were most prevalent in high-income or mid-high-income economies (Fig. 3.3).

(3) Goal Setting and Progress Tracking

Quantitative goals refer to those that are specific and measurable, set by an initiative or its members, ranging from emissions reduction and climate finance to capacity-building, etc.

Monitoring reporting and verification practices for individual ICIs are fragile. On the Climate Initiative Platform, less than 23% of ICIs featured regular monitoring or reporting mechanisms. Other studies have also revealed that the percentage of initiatives with established monitoring and reporting mechanisms is relatively low.

As the type and rigor of monitoring requirements vary dramatically between city-focused initiatives, many do not carry out or share cost estimates or feasibility studies, adding additional obstacles to feasibility assessment and potential barrier identification. Efforts are needed to gather “more and better” data from initiatives to facilitate the assessment of ICIs progress and forecast of its contribution to sustainable development.

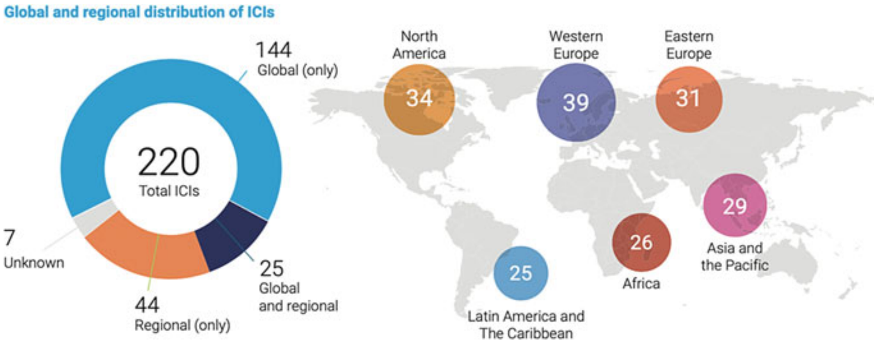

Fig. 3.2 Global and regional distribution of ICIs. *Source* UNEP. Emissions Gap Report 2018

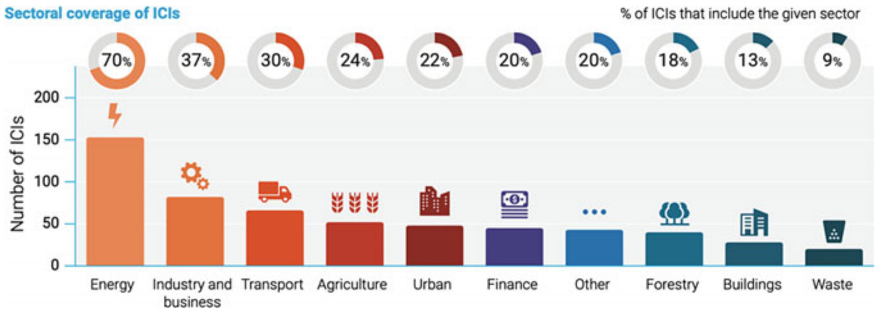

Fig. 3.3 Areas of focus of ICIs. *Source* UNEP. Emissions Gap Report 2018

3.1.3 Progress Towards Carbon Peak Targets in Major Chinese Cities

China has pledged to peak emissions by around 2030 and strive to secure an earlier peak. In June, 2015, China submitted to the Secretariat of UNFCCC its intended nationally determined contribution (INDC)—Strengthening Actions on Climate Change, which confirmed its NDC targets by 2030, including the peak of CO_2 emissions by around 2030 and efforts to hit the target well before the timetable, cut in CO_2 emissions per unit of GDP by 60–65% from the level in 2005, the share of non-fossil fuels reaching about 20% of primary energy use, and increase of forest stock by about 4.5 billion cubic meters over 2005, etc. The Outline of the 13th Five-Year Plan for National Economic and Social Development of the People's Republic of China clearly states that by 2020, carbon emissions from key industries such as electricity, steel, building materials and chemicals should have been curbed; low-carbon development in key sectors such as industry, energy, construction and transportation should be facilitated; support should be provided to priority development areas to show leadership in peaking emissions; low-carbon pilot projects should be advanced and near-zero emission demonstration projects conducted.

Great disparities exist in the peak targets and implementation progress at the provincial level. All 31 provinces, autonomous regions and municipalities have unveiled proposals or plans for curbing greenhouse gases emissions during the 13th Five-Year Plan period, with targets varying from place to place, as surveys found. Twenty-one cities and two provinces and autonomous regions have announced their own targets for peaking CO_2 emissions, accounting for 17% of China's population, 28% of its GDP and 16% of its total CO_2 emissions. Some other provinces (autonomous regions and municipalities) did not set province-wide timetable for the peak, but defined targets for key regions, pilot cities or major industries in light of realities on the ground. Others that did not give any targets at all have conducted studies on peak of carbon emissions according to their own needs (Figs. 3.4 and 3.5).

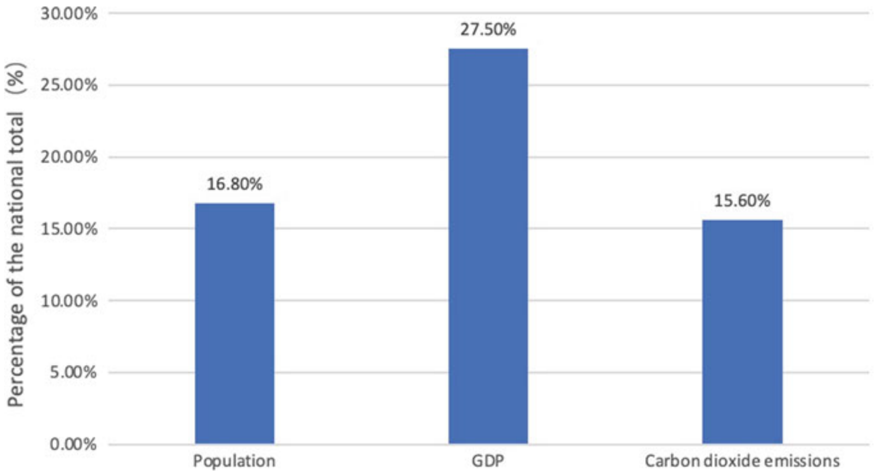

Fig. 3.4 Permanent residents, GDP and CO_2 emissions in China's peak pioneering cities as a percentage of national total

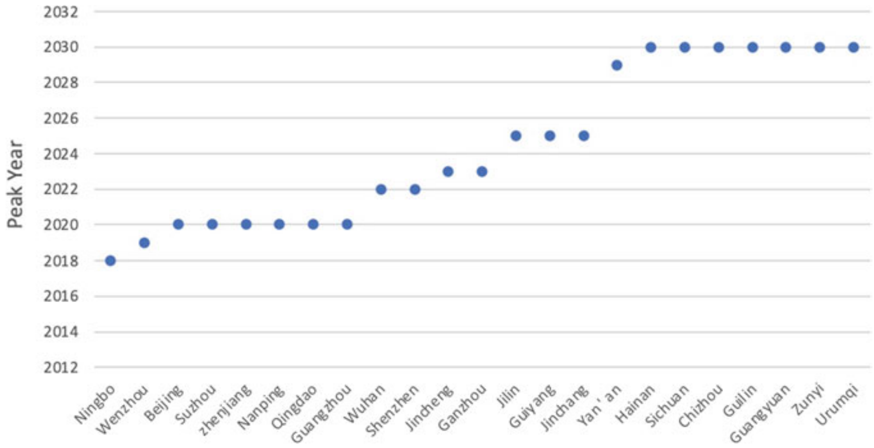

Fig. 3.5 Targets of peak pioneering cities in China

3.1.4 Key Initiatives for China's Major Cities to Reach Carbon Peak Target

Initial findings from the assessment on emission peak targets and implementation in three economic developed provinces (municipalities) of Beijing, Shanghai and Guangdong have suggested that the combined economic size of the three places as a percentage of national economy was greater than their share of carbon emissions in 2017. Due to the varied focus and approach of economic growth, the three also have

Table 3.2 Peak targets of major cities (Plan for Energy Conservation and Response to Climate Change during the 13th Five-Year Plan Period, Shanghai Urban Master Plan (2017–2035), Work Plan for Curbing Greenhouse Gas Emissions during the 13th Five-Year Plan Period, 2018 China Statistical Yearbook)

	GDP (2017)/100 mil yuan	Total carbon emissions (2017)/100 mil tons	Peak forecast	References
Beijing	28,014.9	1.5	Hit the peak in 2020 and strive for an earlier peak	*Plan for Energy Conservation and Consumption Reduction and Addressing Climate Change during the 13th Five-Year Plan Period*
Shanghai	30,632.99	2.913	The city's total and per capita carbon emissions will peak before 2025, and by 2035, the total emissions will be down by about 5% from the peak	*Shanghai Urban Master Plan (2017–2035)*
Guangdong	89,705.23	7.945	Will be among the first to hit the peak before 2030, without specific timetable	*Work Plan for Curbing Greenhouse Gas Emissions during the 13th Five-Year Plan Period*

exhibited distinctive features in their ways of curbing greenhouse gases emissions and reaching the peak (Table 3.2).

After the national release of the Outline of the 13th Five-Year Plan, the above three provinces (municipalities) have formulated medium and long-term carbon emission targets, which have been assigned to each area and sector throughout the hierarchy to encourage structural adjustment and upgrading of key areas and energy-intensive industries, so as to facilitate the peaking process (Table 3.3).

Table 3.3 Analysis on the reality of promoting earlier emission peak in some regions, Cao et al. (2019)

	Upgrade industrial structure	Optimize energy mix	Building sector	Transportation sector
Beijing	Tightly control the number of existing and new enterprises; prioritize the tertiary industry	Promote clean and low carbonization of four major gas-fired CHP(combined heat and power) centers Enhance application and development of local renewable energy sources; accelerate the construction of external green power channels	Strictly control the size of buildings; strengthen energy-saving renovation of existing buildings; increase efforts to replace coal with gas or electricity	Increase the share of clean energy vehicles Control the number of motor vehicles Develop smart traffic technologies, etc.
Shanghai	Vigorously develop advanced manufacturing and modern service industries Strictly control the size and energy consumption of heavy and chemical industry Intensify efforts to adjust backward production capacity	Aggressively reduce total coal consumption; increase the proportion of low-carbon energy sources such as natural gas	Actively promote prefabricated building Facilitate technical applications of municipal infrastructure	Increase the share of green mobility Promote low carbonization of air and water transportation
Guangdong	Focus on curbing industrial emissions Phase out outdated capacity in energy-intensive industries and strictly control new capacity Rein in energy-intensive sectors as a percentage of the secondary industry Spur low carbonization of export structure	Strictly rein in increase of coal consumption Enhance technologies of coal-fired power plants, shut down more existing coal-fired units, and tightly control new such facilities (Implementation Plan of Energy Structure Adjustment during the 13th Five-Year Plan period of Guangdong Province.)	Advance energy-saving renovation of existing buildings Strengthen energy conservation efficiency in new buildings Promote green building	Facilitate the development of a modern comprehensive transportation system Accelerate the development of low-carbon railway and waterway, etc. Improve urban transport system with public transport first encourage the use of energy-saving, clean energy and new energy transport

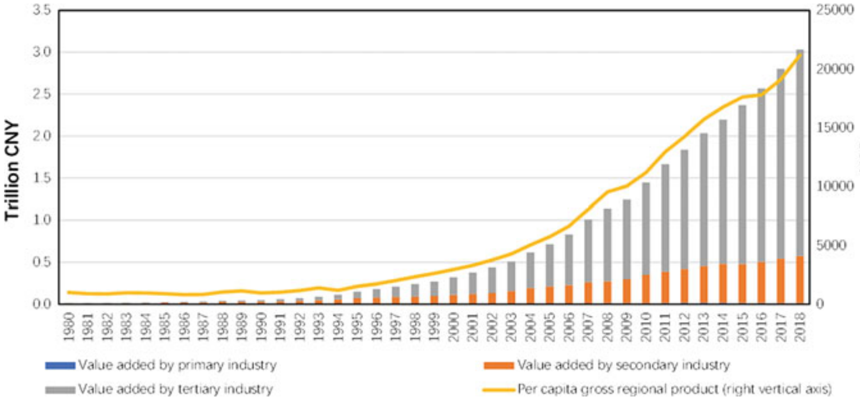

Fig. 3.6 GDP in current prices of Beijing (1980–2018). *Source* Beijing Municipal Bureau Statistics and Survey Office of the National Burea of Statistics in Beijing (2019)

3.2 Beijing's Energy Demand and Challenges to Achieve Its CO_2 Emission Peak Target[2]

3.2.1 Current Situation of Energy Consumption in Beijing

Beijing is the capital of China, the political center of China, the cultural center of China, the scientific and technological innovation center of China, as well as a hub of international exchange of the world. It has explicitly stated its policy goal of peaking emissions by 2020 and striving for an early peak in the *Plan for Energy Conservation and Consumption Reduction and Addressing Climate Change during the 13th Five-Year Plan Period*, showcasing the political will to proactively tackle climate change. Beijing serves as an exemplar model for its peers in China, and are therefore selected for a major case study in this research.

Beijing has entered the phase of post-industrial development. Its per capita GDP surged from about 1009 US dollars in 1980 to 21,188 US dollars in 2018, up by nearly 20 times. Its value added of tertiary industry as a percentage of GDP soared from about 27% in 1980 to over 80% in 2018 (Fig. 3.6). Its total energy consumption jumped from 19.08 million tce in 1980 to about 73 million tce in 2018. During the same period, energy intensity saw a sharp decline from nearly 14 tce per 10,000 Chinese Yuan (CNY) in 1980 to less than 0.3 tce per 10,000 CNY in 2018 (Fig. 3.7).

At present, Energy consumption in Beijing is characterized by:

First, coal is no longer the main form of energy use in Beijing, with its consumption plummeting from 18.8 million tce in 2010 to 4 million tce in 2017 (Fig. 3.8), when

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[2] Authors of this section: Shiyan Chang, Siyue Guo, Hongyu Zhang.

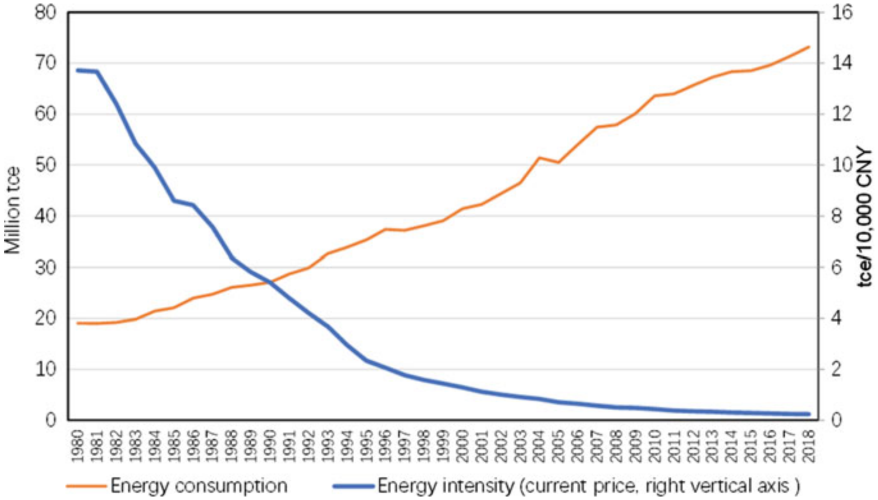

Fig. 3.7 Total energy consumption and Intensity of Beijing (1980–2018). *Source* Beijing Municipal Bureau Statistics and Survey Office of the National Burea of Statistics in Beijing (2019)

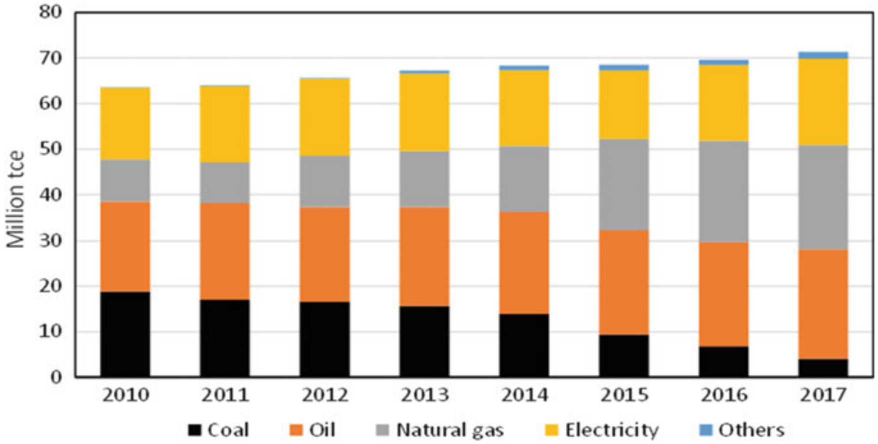

Fig. 3.8 Energy consumption by fuel type in Beijing (2010–2017). *Note* Electricity here refers to the sum of net imported electricity and domestic non-fossil fuel power generation. *Source* Beijing Municipal Commission of Development and Reform et al. (2018)

coal accounted for only 6% of the city's total energy use. Coal consumption in Beijing fell to the lowest in the country in 2017.[3]

Second, natural gas consumption has soared as the main form of energy use in Beijing. It jumped from 7.5 billion cubic meters in 2010 to 16.5 billion cubic meters in 2017, accounting for over 30% of the total energy use in the city. Beijing is now the

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[3] Compared with that of other 29 provinces included in the China Energy Statistics Yearbook.

fourth largest natural gas consumer in China, after Jiangsu, Sichuan and Guangdong provinces.

Third, oil consumption has seen continuous growth, rising from 14.55 million tons in 2010 to 16.56 million tons in 2017. But the growth is not primarily attributed to the use of gasoline and diesel, which are mainly used for road transportation, and dropped from 3.72 million tons and 2.37 million tons respectively in 2010 to 1.9 million tons and 1.75 million tons in 2017. The city has seen some modest increase in the consumption of kerosene, which is mainly used for air transport and climbed from 3.93 million tons in 2010 to 6.44 million tons in 2017. Beijing's kerosene consumption in 2017 matched that of Shanghai, with the two cities accounting for about 36% of China's total kerosene consumption**.**

Fourth, local renewable energy is not adequately utilized. In 2015, the development and utilization of new and renewable energy in Beijing was about 4.5 million tce, which only made up 6.6% of the total energy consumption (Beijing Municipal Government 2017), much lower than the national level in the same period.

Fifth, the net import of electricity represents a relatively high proportion. In 2017, it comprised more than 25% of the total energy use, and accounted for over 60% of electricity demand of the entire city.

It can be seen that in recent years, Beijing's energy system is undergoing a profound low-carbon and clean transformation, which benefits from a range of measures implemented by the city in addressing climate change and air pollution, especially the control on coal consumption. (Fig. 3.9).

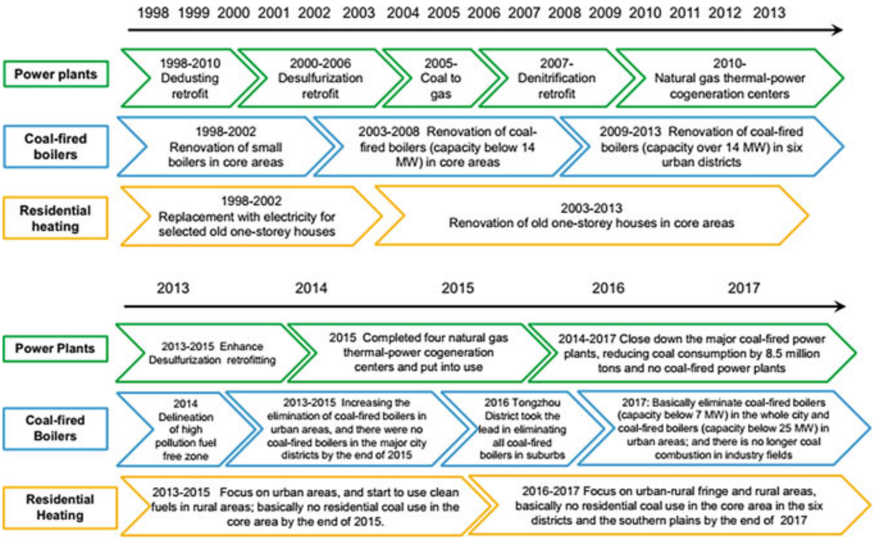

Fig. 3.9 Coal control measures in Beijing (1998–2017). *Source* United Nations Environment Programme (2019)

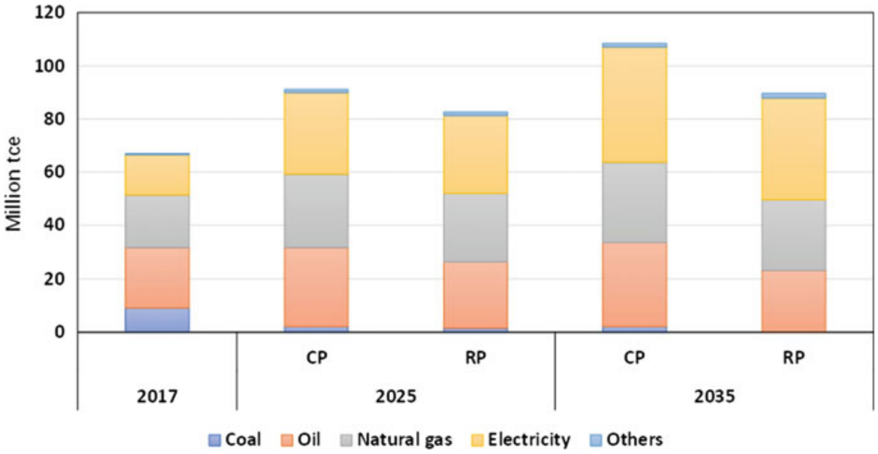

Fig. 3.10 Energy consumption projection in Beijing. *Note* Electricity here refers to the sum of net imported electricity and domestic non-fossil fuel power generation

3.2.2 Medium- and Long-Term Energy Demand and CO_2 Emission

This research seeks to analyze the medium-and-long term energy transformation in Beijing by creating two scenarios: current policy (CP) scenario and reinforced policy (RP) scenario, the former being the continuance of current policies or development, and the latter being the strengthening of certain measures to ensure the peak in 2020 and the target for total energy consumption by 2035.[4]

Research on the scenarios shows that Beijing is expected to see moderate growth in energy consumption and enhanced energy mix from 2015 to 2035. Under the CP scenario, energy use might total 100 million tce in 2035; while under the RP scenario, the figure was around 90 million tce, which is aligned with the target in the *Beijing Urban Master Plan (2016–2035).* Under the RP scenario, coal consumption would continue to fall sharply and arrive at a near-zero point after 2030. The consumption of oil and gas will hit around 16 million tons and 20 billion cubic meters respectively in 2035. Electricity consumption will soar to roughly 180 TWh by 2035, or 7800 kWh per person. From 2015 to 2035, the total consumption of oil, gas and electricity as a percentage of the city's total energy consumption will rise from 87% to 99%, with renewable energy accounting for 20%. Energy use in different scenarios is shown in Fig. 3.10.

Different scenarios imply varied CO_2 emissions in Beijing. Considering the embodied CO_2 emission of imported electricity, the CO_2 emissions will see a continued growth until 2030, with a peak of about 170 million tons by 2030 under

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[4] In the Beijing Urban Master Plan (2016–2035), it indicates that the city will strive to keep total energy consumption at around 90 million tce by 2035.

the CP scenario; while under the RP scenario, the peak of CO_2 emission can be seen before the year of 2020.

3.2.3 Key Challenges for Achieving Beijing's CO_2 Emission Peak Target

Coal burning is no longer the main source of carbon emissions in Beijing, accounting for only 8% of the city's total CO_2 emissions in 2017. As Beijing increasingly becomes coal-free, CO_2 emissions from coal burning will furtherly decline, paving the way for its early peak target. However, the drop in coal use does not imply a smooth sailing for the 2020 peak. While standing at a new start of energy transformation, Beijing still faces challenges to achieve the peak target by 2020.

3.2.3.1 High Proportion of the Building Sector in Energy Consumption

In 2017, total energy use in the building sector of Beijing was about 34 million tce,[5] accounting for 47.6% of the total in the city, much higher than the industrial and transportation sectors, making it the largest energy consumption sector in the city. The building sector in Beijing consumed 3.53 million tons of coal, 7.9 billion $m^3$of natural gas and 68.4 billion kWh of electricity, representing 72%, 48% and 64% of energy consumption respectively. Per capita energy use of the sector was 1.6 tce/cap, and energy use per unit of square meter was 32 kgce/m^2, both higher than the national average, but lower than developed countries, as shown in Fig. 3.11. Therefore, the per capita energy consumption of the building sector still has space for growth in the future.

In 2017, the size of civil buildings in Beijing totaled about 1.06 billion m^2, and the per capita residential space was 32 m^2/cap, which was close to the national average. In recent years, with the stable urban construction in the city, the building spaces have also been stabilized, with new spaces mainly added to upgrade living environment, improve residential amenities, and enhance Beijing's functional development. Based on the long-term population and urban function planning of Beijing, it's projected that by 2035, the inventory of buildings will amount to 1.5 billion m^2, including 690 million m^2 of urban residential buildings, 180 million m^2 of rural residential buildings, and 630 million m^2 of public and commercial buildings.

Given the trends of Beijing's actual energy use and potential control measures, we can calculate the energy consumption of building sector under varied scenarios. Under the CP scenario, consumption would continue to grow, and slow down after 2030 to register at around 52 million tce by 2035; while under the RP scenario, it would peak by around 2030, and hit 45 million tce by 2035, which is 7 million tce less than that of the CP scenario. Electricity and gas are the main forms of energy

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[5] The electricity consumption is calculated by coal equivalent.

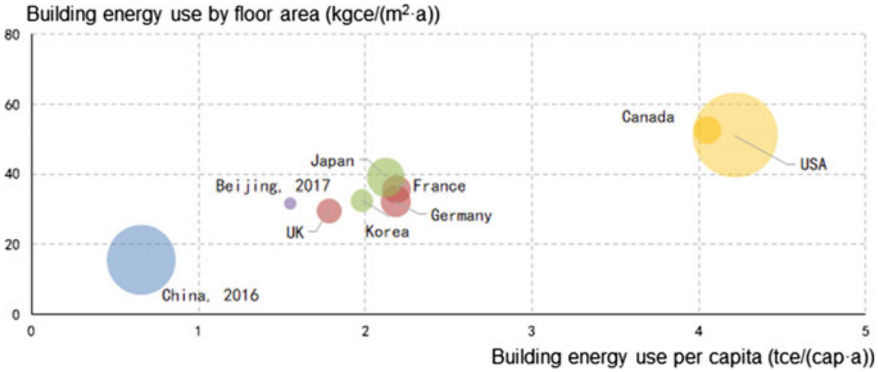


Fig. 3.11 Comparison of building energy consumption between Beijing and other regions. *Note* National data is quoted from Building Energy Efficiency Research Center of Tsinghua University (2017), and Beijing's data is calculated by the authors; The size of the bubbles represents the total energy consumption of building sector in each region

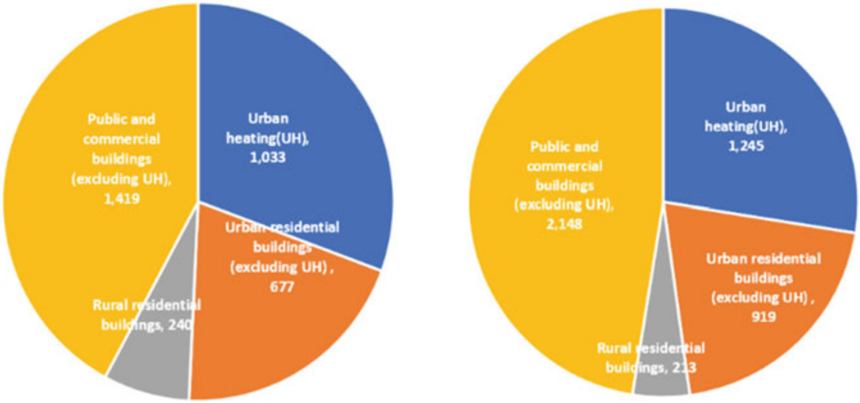
consumption in the building sector. Under the RP scenario, gas consumption in the sector will reach 11.4 billion cubic meters in 2035, an increase of 3.5 billion cubic meters from 2017.

Public and commercial buildings (excluding Urban Heating) is and will continue to be the primary energy user in the building sector of Beijing until 2035 with a growing share of energy use. Energy consumption of urban residential buildings (excluding Urban Heating) would keep rising until 2025 when it hits the plateau and remains ever since. Energy use of urban heating (UH) would continue with a slight growth due to expanded access to heating despite falling energy intensity per unit of heating space. And energy consumption of rural residential buildings would drop as rural population dwindles, as shown in Fig. 3.12.

3.2.3.2 Oil Consumption from Road Transportation to See Continuous Decline, Yet that from Aviation Would Rise Fast

In 2017, about 20.53 million tce energy was consumed in the Beijing's transportation sector (including aviation, postal, railway, cargo transportation, sanitation and private transport). In the future, the inelastically rising energy demand from city transportation, coupled with improved energy service, would push up further energy use in this regard.

According to related plans and policy documents such as *Beijing Urban Master Plan (2016–2035), Three Year Plan to Win the Blue Sky Defense War of Beijing, Beijing Transportation Development Planning for the 13th Five-Year Plan Period*, electric vehicles are expected to represent a much larger share in the transportation system, considering a variety of key factors including change in vehicle ownership, upgrade of vehicle energy mix, structure adjustment of cargo transportation and



(a) 2017 (b) 2035

Fig. 3.12 Energy consumption by building sub-sectors under the RP scenario (Unit: 10,000 tce)

massive development of rail transit, etc. With the upgraded vehicle energy mix and control on the number of cars in Beijing, the use of gasoline and diesel will be slashed.

However, the rising number of flights stemming from the opening of the new airport would spark soaring demand for aviation kerosene. With the launch of the new airport in 2019, Beijing will see a spike in air passenger flow and demand for kerosene, making air traffic a major energy consumer in future transportation, with an estimated kerosene consumption of 11.42(RP)-13.43(CP) million tons in 2035, accounting for 18%–19% of total energy consumption in Beijing.

3.2.3.3 Electricity Demand Continues to Rise, Despite Limited Renewable Energy Resources in Beijing

In 2017, the total electricity consumption in Beijing stood at 106.69 TWh, with a per capita consumption of 4915 kWh per capita. Given increasing electrification of equipment and devices, electricity consumption of the city is expected to grow further, reaching 178.6 (RP)—196.8 (CP) TWh by 2035, averaging 7800–8550 kWh per capita.

The power sector in Beijing has largely been coal-free. In 2017, the installed power generation capacity of natural gas stood at 9710 MW, or 86% of the total power production capacity in Beijing. To maintain low-carbon development of the power sector and ward off another uptick of its CO_2 emissions, efforts should be made to curb gas-fired power production, stop building new gas cogeneration projects, suppress development of gas distributed energy system, and vigorously develop local renewable energy and ensure electricity import.

However, Beijing is hampered by finite local renewable resources, with inadequate wind and hydro power resources. There is potential for geothermal, which is available at 3.5 million tce per year (Beijing Municipal Commission of Development and Reform 2011). Solar is relatively abundant in Beijing. Beijing is listed as a Class II solar resource region (very rich solar resource zone), featuring high annual average irradiance (about 160–200 W/m^2) (Division of New and Renewable Energy of the National Energy Administration and National Renewable Energy Center 2017). But limited available land area implies a measure of uncertainty for the available solar resource being utilized. Given the limited renewable resources on the whole, the production of sufficient renewable power constitutes a major challenge to Beijing on the way of peaking carbon emissions.

Meanwhile, the proportion of imported electricity will continue to be above 60% . With the sustained growth in electricity demand, the quantity of net import would spike from 67.5 TWh in 2017 to 112.16 (RP)—139.33 TWh (CP). While ensuring security and stability of its power system, low-carbon and clean transition presents a key challenge for Beijing in achieving the CO_2 emission peak.

3.2.4 Key Suggestions on CO_2 Emission Reduction Measures

3.2.4.1 Further Promote Energy-Saving and Energy Substitution in Building Sector

The building sector needs to take multi-pronged steps to facilitate the peak by 2020, including boosting building energy efficiency and scaling up low-carbon and clean energy alternatives. Current energy conservation efforts in China are gradually moving from intensity control to a blend of such control with a cap on total energy use. The target on limiting the total energy consumption of civil buildings within 41 million tce by 2020 has been put forward in the ***13th Five-Year Plan for the Development of Energy-saving Civil Buildings*** issued by the Beijing municipality. Based on our calculation, the energy consumption of building sector can be kept at about 42.5 million tce in 2025 and 45 million tce in 2035 through proper control measures and guidance. A stricter cap on total energy use can be defined in relevant plans to boost energy conservation in the building sector.

Public and commercial buildings (excluding UH) represent the largest energy consumer among the four sub-sectors of the building sector in Beijing, and energy intensity in this component has hit a plateau, meaning that future energy saving should mostly come from energy intensity caps and efficiency improvement. Beijing has unveiled the *Civil Building Energy Consumption Targets (draft for comments)* for almost all forms of public buildings, providing the standard to exercise effective management on capping energy use of buildings. Going forward, the city should step up enforcement of the standard.

The reduction of energy consumption in urban heating can be achieved by improving the inherent performance of the building, reform of the thermal system and optimizing of the heat source. In a bid to cut energy use in the building sector, Beijing has released the 75% energy-efficiency standards, and has drafted the 80%

standards, which would unlock up to 80% energy savings for all new buildings in the future. In 2017, 180 million m^2 of urban buildings in Beijing were not upgraded for energy savings. It is estimated that 90 million m^2 of building will be renovated by 2025, with an annual renovation of 10–15 million m^2. By 2035, some 60 million m^2 public buildings will continue to be upgraded, or 5–10 million m^2 per year. It is scheduled that by 2035, the city will be completely heated by gas, heat pump and waste heat, etc. The following measures could be taken to upgrade the heating system:

(1) tap into the waste heat utilization of flue gas of natural gas boiler to improve the heating capacity of existing system;
(2) pursue the synergy between heat and power of power plants. Gas-fired power plants should operate under variable load in a day according to requirements of load dispatching, and balance the change in power generation and stable heat supply;
(3) combine green electricity consumption with full use of local waste heat resources to enable efficient clean heating and replace and reduce natural gas consumption in heating. Such resources as waste water heat from sewage treatment plants and waste heat from garbage incineration are available in Beijing;
(4) transmit recovered waste heat from large power plants or industry plants in surrounding provinces to Beijing. When the transmission distance of a heat network is less than 200 km, the cost of heat supply from outside is likely to lower than that of the gas boiler. Several heat sources close to Beijing can be considered, including several power plants in Sanhe, Panshan, Beijiang and Zhangjiakou;
(5) transmit recovered waste heat under large temperature difference through heat network; the technology is already matured;
(6) the existing independent gas boilers can be integrated into the large heat network to adjust the peak of heat sources, such as the aforementioned thermal power plants and those from outside of Beijing that utilize industrial waste heat.

3.2.4.2 Facilitate Energy Saving and Fuel Replacement in Transport Sector

Beijing has taken a slew of measures to promote energy conservation and fuel replacement in the transportation sector. More efforts could be made to encourage and incentivize fossil-fueled car owners to convert their vehicles into electric ones to drive up electrification of cars. It is estimated that in 2035, private new energy vehicles would reach around 2.5 million, or 43% of the total vehicle stock.

In the meantime, energy conservation and CO_2 reduction measures in the aviation sector need to be strengthened. The energy and CO_2 emission management of key aviation enterprises should be further strengthened, and the research, development and demonstration of aviation biofuels are encouraged.

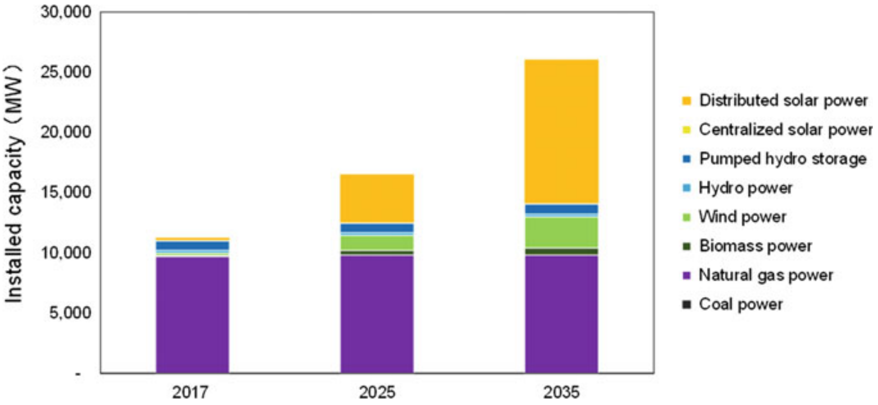


Fig. 3.13 Power installed capacity in Beijing under the RP scenario

3.2.4.3 Vigorously Boost Distributed Solar and Other Renewables

Promoting the use of renewable energy can effectively reduce the combustion of fossil energy and cut CO_2 emissions. After 2020, newly built power stations in Beijing should be mainly based on new energy and renewables. Given the potential of renewable resources in the city, major steps should be taken to ramp up distributed renewable energy system. In particular, solar power production should be scaled up by fully utilization of building roofs, walls, green field and greenhouses, etc. These efforts is projected to promote the installation of renewable energy in Beijing up to 16.2 million kW in 2035, or 70% of the total power capacity in the city, of which distributed solar would reach approximately 12 million kW under the RP scenario, or over 50% of the total (Fig. 3.13). Under the same scenario, the share of gas power genertion in the electricity consumption of Beijing would fall from 34.6% in 2017 to 21.5% in 2035, while that of renewables would surge from about 2% in 2017 to 16.6% in 2035 (Fig. 3.14).

Beijing has launched a batch of policy measures to promote the renewable energy development. For example, a policy initiative, known as the “Five Sunshine” initiative, has been launched to promote over a million-kilowatt solar power in campus, business, industry, agriculture and infrastructure during the 13th Five-Year-Plan period. Economic incentives have been adopted to boost distributed solar power, for example, a subsidy of 0.3 CNY is rewarded for each kilowatt hour according to *the Distributed Solar Reward Management Method in Beijing*. Enhanced incentives for distributed energy to further tap into renewable energy in the city are necessary.

3.2.4.4 Increase Import of Green Electricity

Despite the steady mid-and-long term growth of local renewable power as a percentage of electricity demand in Beijing, its overall share is still fairly low.

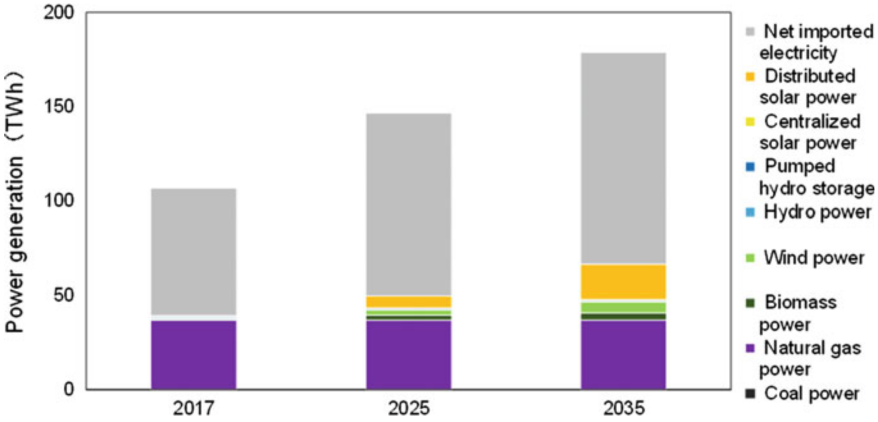


Fig. 3.14 Power generation in Beijing under the RP scenario

To achieve low-carbon and clean transition of the power system while ensuring safety and stability, large quantities of power, especially renewable power, should be imported to Beijing, rather than entirely relying on local renewables.

Extraordinary plans should be made to feed green electricity into Beijing, which might include: step up energy cooperation in the Beijing-Tianjin-Hebei and its surrounding areas and support the construction of large-scale renewable energy bases around Beijing; reinforce the building of green electricity transmission lines. By 2020, over 10 TWh of green electricity will be imported from other provinces, and green electricity will be given preference for new import electricity after 2020.

3.3 Impact of Carbon Pricing Policy in Beijing[6]

3.3.1 Features of Carbon Market Pilot in Beijing

3.3.1.1 Full Coverage

There are 943 key emitters in the carbon emission trading market in Beijing, covering seven industries including power, heat, cement, petrochemical, transportation, other industries and service, as well as public institutions such as universities, hospitals and government agencies.

As of October 17, 2019, 35.88 million tons of carbon allowances had been traded, amounting to 1.46 billion yuan. 5227 transactions had been conducted online, involving 13.4 million tons with a worth of 800 million yuan and an average price of

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[6] Author of this section: Jian Zhou.

59.63 yuan/ton (the highest out of 7 pilots). The price had shown a stable trajectory, indicating balanced supply and demand.

3.3.1.2 Creation of a Top-Down Legislative Framework

In designing the carbon emission trading system, Beijing has taken the following principles into account: first, it should accommodate the urgent need of environment improvement in Beijing and the whole country to synergize with policies of environmental goverance. Second, harness the local legislative power of Beijing to galvanize local people's congress to pass the "Decisions of the Standing Committee of the National People's Congress", providing legal basis for carbon emission trading. Third, a two-pronged approach should be adopted for the legislation, meaning that legal basis set up by local people's congress should be complemented by "management measures" issued by local governments to clarify key elements in legislation. Fourth, competent authorities should formulate documents to identify the procedures and timetable for implementation. Beijing did exactly the same by taking the following two steps. For starters, it passed "decisions" to provide legal safeguard for carbon emission trading pilot in Beijing, which was then followed by the issuance of "regulation" through local government to offer a reliable legal safety net for the healthy development of carbon emission trading in the city.

Beijing has put in place a two-tiered legislation model featured by a blend of "decisions" passed by local people's congress and "management measures" issued by local government, which represents the ideal legislative approach. For one thing, "decisions" of local people's congress helps identify carbon emission permit, set up a framework of emission control and trading, and strengthen the effectiveness of penalty. For another, "management measures" drafted by local government further define the process and procedures of trading.

Beijing has been at the forefront of capping carbon emissions and spearheaded the "cap-and-trade" scheme, which were stipulated in the "decisions" of the local people's congress and the "implementation plan" of carbon emissions trading.

3.3.1.3 The Fusion of "Visible Hands" and "Invisible Hands"

1. Fully accommodate the need of transferring non-capital functions of Beijing and reasonably determine the coverage of control.
   The emission allowance allocation methods comprise "grandfathering", "historical intensity" and "benchmarking", the choice of which determines the incentive recipient of the emissions trading policy. Currently, carbon market in Beijing applies a mixture of the three approaches, using "grandfathering" for manufacturing and service, "historical intensity" for heating suppliers, and "benchmarking" for power suppliers and new facilities. The allowance is allocated to producers and suppliers (organizations) of heat and power, manufacturers, mining enterprises and service providers (organizations) due to the reasons below:

First, Beijing learned valuable experience from the EU emissions trading system. The EU ETS phase I (2005–2007), for example, sectors covered by EU ETS included energy supplies, oil refining, steel, building material and paper making; phase II included electricity and heat production, steel, oil refining, chemical, glass, ceramics, building materials (incl. cement), paper making and printing (incl. pulp); and the third phase covered aviation, chemical, ammonia and aluminum.

Second, it helps fulfill the central government's pledge to curtail coal consumption in the Beijing-Tianjin-Hebei region and create synergy between PM2.5 and smog control. As per the city's *Work Plan on Accelerating Coal Reduction and Improving Air Quality*, the total coal consumption in Beijing will be reduced to less than 10 million tons by 2020. Therefore, inclusion of the above sectors and businesses in the scope of BJETS will prompt key emitters to actively renovate their coal-fired boilers.

Third, by building carbon market, it helps curb total energy consumption by key energy users in Beijing. *The 2017 Energy Utilization Bulletin of Beijing's Key Energy Users* shows that in 2017, there were 521 workplaces that consumed 5000 tons of coal equivalent (and above) in Beijing, including 173 key industrial users and 348 non-key industrial users. Most key energy users also represent key carbon emitters in the city, thus required mandatory participation in the emission trading system. By limiting carbon emissions from these places, Beijing is on right track to achieve its goal of reducing energy intensity per unit of GDP by the end of the 13th Five-Year Plan period.

2. Align with Beijing's plan for industrial restructuring and optimization of its energy mix when defining the emission control coefficient.

   The methodology for determining emission control coefficient is: firstly, determine the ceiling of total carbon emissions from each sector/industry involved in allowance allocation based on the statistical data of historical years, control target or data in the planning of a given allocation period; then break down the emission ceiling into two parts: allowance cap of the operational production capacity prior to the allocation period and that of the allowed new production capacity during the allocation period; finally, divide the allowance cap of operational capacity by grandfather emissions (the average annual emissions in the historical base year) to obtain the coefficient for varied sectors and industries.

3.3.1.4 Reinforced Safeguard for Compliance

Experience of carbon trading pilot suggests that such factors as the legal system and policy enforcement bear considerable impact on the compliance rate.

1. Put carbon trading on a higher legislation level by imposing government penalties on the violations of enterprises under the scheme in order to deter non-compliance.

   In the absence of host law support, if the pilot is only regulated by general documents without forceful legislation by the National or Local People's Congress, authorities of carbon trading would have their hands tied when formulating penalty measures as no heftier fines could be levied, hence no deterrence for violations.

As per the *Decisions on Carbon Trading Pilot under the Premise of Strictly Capping Carbon Emissions* adopted at the 8th Session of the 14th Standing Committee of Beijing Municipal People's Congress on December 27, 2013, failure to submit carbon emission report or third party verification report shall be rectified by the competent department overseeing climate change under the Municipal People's Government; overdue rectification shall incur a fine of not more than 50,000 RMB yuan; If a key emit makes emissions beyond the permitted allowance, the competent department of climate change shall order it to fulfill the responsibility of emission control within a time limit, and may be punished according to the amount of carbon emission exceeding the permitted allowances according to 3–5 times of the average carbon market price. In the first year of compliance (2014), 97.1% of the 415 key emitters complied on their own accord, and the 12 emitters that failed to do so were punished with a fine 3–5 times of the average carbon market price in strict according with the regulation. Over the first six months of 2014, carbon allowances were traded at 54.57 RMB yuan/ton on average, so non-compliant emitters in Beijing were fined 164 RMB yuan/ton, 218 RMB yuan/ton and 273 RMB yuan/ton respectively for their excess emissions of less than 10%, 10–20% and over 20% in 2013. By imposing the heaviest fine on non-compliance, Beijing became a paragon for strict enforcement across the country.

2. Strengthen the Enforcement of Carbon Trading.

The carbon trading system is highly complex and involves a range of industries of economic and social development. How the system is implemented will determine the authenticity of the outcome, thus bearing notable impact on the homogeneity of the allowances. In relative terms, carbon trading policies in Beijing have been rigorously implemented, engaging such stakeholders as authorities, traders, verification institutions and policy advisors, as well as a law enforcement taskforce created for supervising non-compliance and ensuring the data quality of enterprises.

Create detailed rules and taskforces for law enforcement. For instance, Beijing has stepped up supervision on carbon market to prompt compliance, and levied fines 3–5 times of the average carbon market price. *The Provisions on Regulating the Discretion of Administrative Penalties for Carbon Emission Trading* have been issued to confer legal grounds to penalties, impose fines that are commensurate with the breaches, ensure the exercise of comprehensive discretion and the legality and rationality of the discretion in administrative penalties. It also clarified the types and ranges of penalties.

3.3.2 Mechanism for Stablizing Carbon Prices

Economic theories dictate that prices are jointly determined by supply and demand. Carbon trading market is unique in that the supply is determined by the government, and the lack of data and other deficiencies at the outset might often result in a mismatch between supply and demand. Moreover, economy growth may lead to a drop in demand for allowance, and the supply should also be reduced accordingly to maintain price stability. But in reality, the supply dictated by the government has failed to make timely response and adjustment to the changing needs. In addition, trading prices are subject to a variety of factors, including differences in the cost of emission reduction of varied industries, and the size and degree of activity of market players. Experience in most carbon markets, including EU, has pointed to a surplus of allowances during economic downturn. Carbon market has proven incapable of handling such unique "market failure" on its own, and therefore calls for appropriate government intervention.

Carbon trading prices serve as a signal of all economic activities in the carbon market associated with emission reduction. Proper carbon prices can boost low-carbon transition of the economy and enhance incentives in the market. If not, it may worsen the tensions between economic development and emission reduction. Prior to the inception of the pilot, Beijing had mulled over the framework design of price regulation, and has broken new grounds on top of the experience and lessons of EU. To illustrate, it laid out the plan for allowance revision, price control measures and the ceiling and floor of prices, setting an example for pricing control in domestic carbon market.

3.3.2.1 Building Key Scenarios

Carbon market in Beijing should leverage its role of curbing carbon emissions and keep a close watch on carbon prices, forestalling exorbitant prices and the subsequent shock on GDP as well as excessively low prices that might risk losing the impact of internalized emission cost on major emitters.

By the above analysis, allowance allocation schemes devised by the competent authority represent a key issue in carbon price fluctuations. To this end, two different allocation schemes are selected (see Tables 3.4 and 3.5): moderate allowance (Scenario S1) and loose allowance (Scenario S2), the former being the actual plan in Beijing (2013–2015), which has been moderately tightened during the 13th Five-Year Plan period.

3.3.2.2 Findings

Dynamic CGE model simulation was conducted based on the two scenarios, which factored in the changes in carbon trading prices, the macro-economy of Beijing,

Table 3.4 Moderate allowance allocation plan of scenario S1

	2013 (%)	2014 (%)	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)	2020 (%)
Manufacturing and mining	98	96	94	93.5	93.0	92.5	92.0	91.5
Tertiary industry	99	97	96	95.5	95.0	94.5	94.0	93.5
Gas-fired units of CHP	100	100	100	99.5	99.0	98.5	98.0	97.5
Coal-fired units of CHP	99.90	99.70	99.50	99.0	98.5	98.0	97.5	97.0
Gas-fired units of heat suppliers	100	100	100	99.5	99.0	98.5	98.0	97.5
Coal-fired units of heat suppliers	99.80	99.50	99.00	98.5	98.0	97.5	97.0	96.5

Table 3.5 Loose allowance allocation plan of scenario S2

	2013 (%)	2014 (%)	2015 (%)	2016 (%)	2017 (%)	2018 (%)	2019 (%)	2020 (%)
Manufacturing and mining	98.0	97.9	97.8	97.7	97.6	97.5	97.4	97.3
Tertiary industry	99	98.9	98.8	98.7	98.6	98.5	98.4	98.3
Gas-fired units of CHP	100	100	100	99.5	99.0	98.5	98.0	97.5
Coal-fired units of CHP	99.90	99.8	99.7	99.6	99.5	99.4	99.3	99.2
Gas-fired units of heat suppliers	100	100	100	99.5	99.0	98.5	98.0	97.5
Coal-fired units of heat suppliers	99.80	99.7	99.6	99.5	99.4	99.3	99.2	99.1

energy consumption, carbon emissions and other variables before and after the implementation of carbon trading policy.

S2 scenario (loose allowance) S1 scenario (moderate allowance) (Fig. 3.15 and Tables 3.6 and 3.7).

The above results (see Tables 3.6 and 3.7) shows that in the S2 scenario, excessively low carbon price features much weaker intervention on carbon emission control, which makes the policy irrelevant; while in scenario S1, where the control of the existing allocation scheme in Beijing is maintained and tightened moderately during the 13th Five-Year Plan period, the corresponding policy costs are a 0.56% loss in total GDP and a 0.20% loss in GDP growth compared to the scenario of no carbon trading.

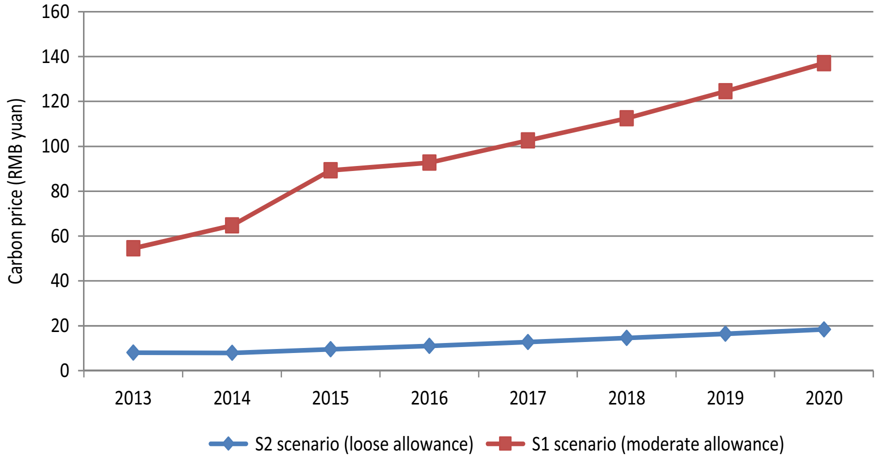

Fig. 3.15 Carbon prices resulting from different allowance allocation scenarios

Table 3.6 Carbon prices in S1 scenario (moderate allowance) and its impact

	2013	2014	2015	2016	2017	2018	2019	2020
S1 scenario	54	65	89	93	103	112	125	137
Carbon price (yuan/t CO_2)	54	65	89	93	103	112	125	137
Change rate in total GDP	−0.29%	−0.38%	−0.56%	−0.65%	−0.73%	−0.78%	−0.83%	−0.89%
Change rate in GDP growth	−0.31%	−0.10%	−0.20%	−0.09%	−0.08%	−0.06%	−0.06%	−0.06%
Change rate in energy intensity compared to 2010			−25.01%					−39.35%
Change rate in carbon intensity compared to 2010			−29.01%					−44.27%

Table 3.7 Carbon prices in S2 scenario (loose allowance) and its impact

S2 scenario	2013	2014	2015	2016	2017	2018	2019	2020
Carbon price (yuan/t CO_2)	8	8	9	11	13	15	16	18
Change rate in total GDP	−0.02%	−0.02%	−0.03%	−0.03%	−0.04%	−0.04%	−0.04%	−0.04%
Change rate in GDP growth	−0.02%	0.00%	−0.01%	0.00%	0.00%	0.00%	0.00%	0.00%
Change rate in Energy intensity compared to 2010			−23.2%					−37.63%
Change rate in Carbon intensity compared to 2010			−24.95%					−40.48%

3.3.2.3 A Proposal for a Trigger Price Range for Open Market Operations

Based on research of the above scenario, it's suggested that a trigger of floor price is created for carbon prices in Beijing in the design of the carbon trading system, whereby a price lower than 20 yuan would trigger a repurchase according to the "decision" of Beijing Municipal People's Congress, and a price higher than 150 yuan would trigger an auction of carbon allowance.

To illustrate, the city could announce the *Administrative Measures on Open Market Operation*: a daily weighted average price above 150 yuan/ton for 10 consecutive trading days should be up for auction; and a repurchase could be conducted when such price is below 20 yuan/ton for 10 trading days in a row.

Table 3.8 Control coefficient of Beijing carbon market

	2013 (%)	2015 (%)	2020 (%)	2030 (%)
Manufacturing and mining	98	94	92	90
Tertiary industry	99	96	94	92
Gas-fired units of CHP	100	100	98	95
Coal-fired units of CHP	99.90	99.50	98	96
Gas-fired units of heat suppliers	100	100	98	96
Coal-fired units of heat suppliers	99.80	99.00	97	95
Transportation			100	98

3.3.3 Analysis on the Impact of Carbon Trading on Carbon Emissions in Beijing

As the nationwide carbon market is being built step by step, the 14th Five-Year Plan period will witness the coexistence of the national carbon market and Beijing local carbon market. And the transport sector has entered the carbon market in Beijing during the 13th Five-Year Plan period.

3.3.3.1 Allowance Allocation Scheme and the Corresponding Carbon Price

The allowance allocation scheme of Beijing carbon market is assumed in the following Table 3.8.

Apply carbon trading to different energy mix optimization policy (E1 and E2) to be combined with the "new normal" economic policy (GII & GIII), one can get four policy scenarios of carbon trading:

BETS1 [G II (mid growth)/E1 (coal reduction)];
BETS2 [G II (mid growth)/E2 (new energy)];
BETS3 [G III (low growth)/E1 (coal reduction)];
BETS4 [G III (low growth)/E2 (new energy)].

The carbon trading model would produce the future carbon prices in Beijing shown below (Fig. 3.16):

3.3.3.2 Analysis on the Impact on Energy Use

Carbon price can, in some measure, impede the growth of total energy consumption. G I II (high growth), G II (mid growth) and G III (low growth) invariably show a reduction in energy use (Fig. 3.17).

In scenario BETS3 and BETS4, total energy consumption would peak in 2025, with energy consumption of approximately 79 million tons of coal equivalent.

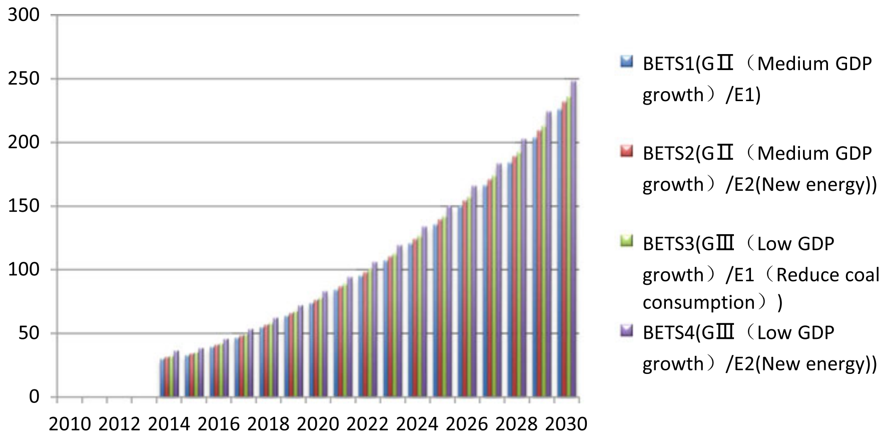

Fig. 3.16 Future trend of carbon prices in Beijing (yuan/T CO_2)

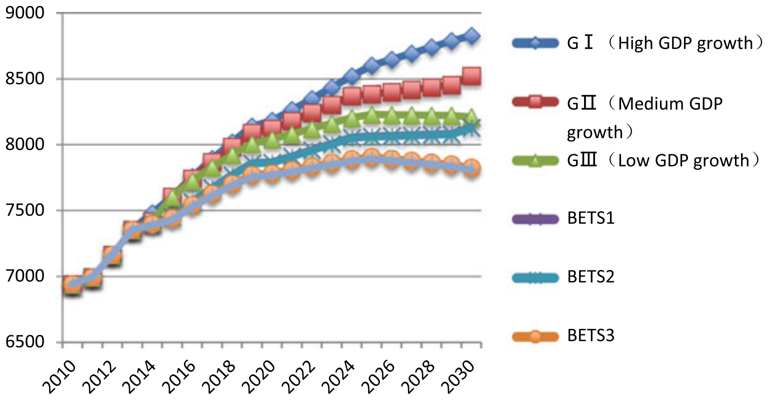

Fig. 3.17 Impact of carbon prices on energy use in Beijing

3.3.3.3 Impact on Carbon Emissions

Carbon price could further curb the growth of CO_2 emissions. G II (mid growth)/E1 (coal reduction), G II (mid growth)/E2 (new energy), G III (low growth)/E1 (coal reduction) and G III (low growth)/E2 (new energy) invariably indicate a drop in CO_2 emissions (Fig. 3.18).

Carbon prices would move up the peak in CO_2 emissions. The above four trading scenarios feature the peaks, which range from 168 to 175 million tons.

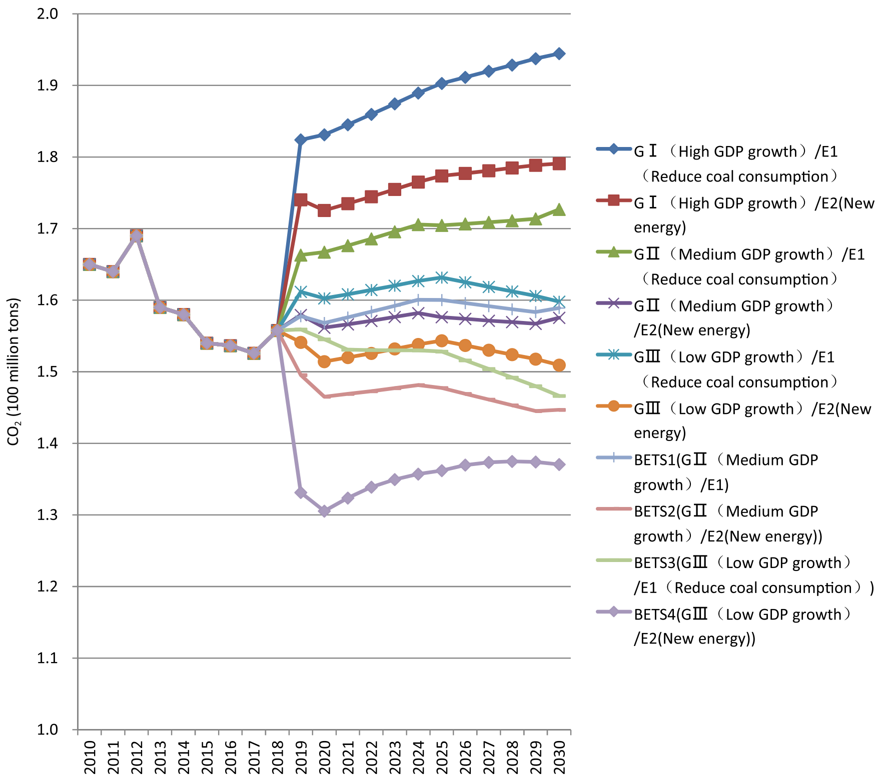

Fig. 3.18 Impact of carbon prices on CO_2 emissions in Beijing

3.4 Conclusions and Policy Recommendations[7]

3.4.1 Major Challenges for Beijing' Low Carbon Actions

1. Growing Resource Constraint Signifies an Inherent Demand for Low Carbon Development and Energy Conservation to Boost Sustainable Development of Beijing.

   During the 14th five-year Plan period, Beijing will witness rapid economic and social development, accelerated urbanization, continuous expansion of building size, and surging traffic volume, prompting a spike in energy demand and a worsening of energy shortage, as evidenced by over 90% dependence on energy import and less than 200 cubic meters of per capita water resource in the city, or 1/35 of the world's average. With the booming urban development, overpopulation and water shortage, Beijing would increasingly fall short of energy demand.

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[7] Authors of this section: Jian Zhou, Shiyan Chang, A'lun Gu, Lingling Zhou.

The city's chronic smog in recent years has also, in some measure, tarnished the reputation of the city and the country as a whole.

2. The Revolution of Energy Production and Consumption has Put Higher Demand for Beijing's Energy Conservation and New Energy Utilization.
   The pattern of energy use in Beijing is undergoing major shifts, with the service industry and residential consumption making up over 60% of the total and becoming major energy consumers. Unlike others, such consumption is scattered across the large expanse of the city, thus calling for intensive research on more energy-saving tools and measures. In the meantime, hampered by its resource endowment, long cycle of project construction and other factors, the city struggles to increase the uptake of new and renewable energy. Therefore, it's essential to promptly roll out projects for the utilization of new and renewable energy. Advancing the revolution of energy production and consumption represents the ultimate solution and key avenue for building ecological civilization and securing low-carbon growth. It's important to shift away from the traditional energy strategy that prioritizes energy supply to guide and regulate energy demand with the aim of building ecological civilization, and vigorously boost new and renewable sources of energy.
3. The Strategic Positioning of Beijing and Coordinated Development of Beijing-Tianjin-Hebei Region Puts Higher Demands for Low-carbon Development
   Green and low-carbon development is part and parcel and a strategic measure for Beijing to strengthen the city's strategic positioning as the "four centers" of China, to build a world leading harmonious and livable city, and to promote the coordinated development of the Beijing-Tianjin-Hebei region. During the period of the 13th Five-Year Plan, energy conservation, emission reduction and carbon reduction has been indispensable for accelerating the transfer of non-capital functions of Beijing, boosting the quality and efficiency of economic growth, and intensive treatment of "metropolitan malaise". All these require greener and lower carbon footprint of the city.
4. The National and Beijing's Commitment to Emission Reduction Determines the Urgency of Building an International Low-carbon City
   During the 2014 APEC Beijing Meeting in Beijing, China and the United States issued the *Joint Statement on Climate Change*, in which China pledged to peak carbon dioxide emissions by around 2030. At the first China-US Climate-Smart/Low-carbon Cities Summit, Beijing set a goal of peaking emissions 10 years ahead of the rest of the country. The 2022 Beijing Winter Olympics bidding report also clearly stated the goal of neutralizing carbon emissions from the 2022 Winter Olympics. To honor its commitment to the Winter Olympics, Beijing must fully embrace the notion of sustainable development, create a better ecological environment and score new achievements of green and low-carbon development of Beijing.

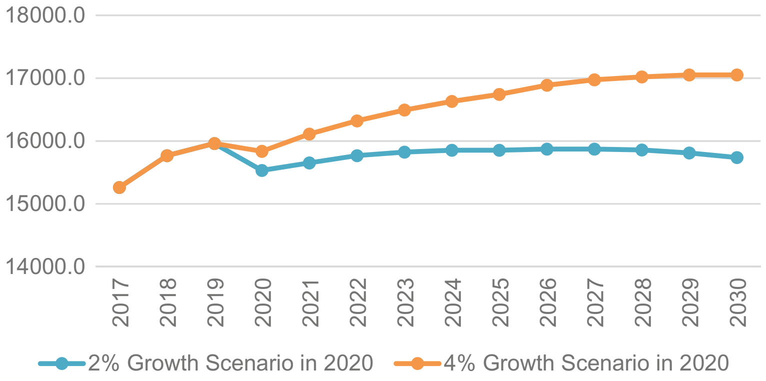

Fig. 3.19 COVID 19 impact on Beijing's emission peak target

3.4.2 Combat COVID19 with "Green Recovery"

The global spread of COVID-19 in 2020 has taken a heavy toll on the world economy. Major international agencies have revised downward global and China's GDP growth for the year. In its "benchmark" forecast for China, the World Bank expects GDP growth to slow to 2.3% in 2020 and to 0.1% in the worst-case scenario. S&P revised down China's GDP growth forecast to 2.9% in 2020. The IMF lowered its projections. Major Chinese institutions also gave their 2020 predictions, ranging from 2% at worst and 4% at best.

The impact on Beijing's goal of peaking carbon emissions: the amount of emissions in 2020 is expected to be down by 0.8–2.7% from 2019, but 2021 would likely see a return to the level of 2019. However, it should also be noted that the emission reduction of Beijing in 2020 is not achieved under normal low-carbon transformation, and the city should guard against a rebound of emissions as its economy recovers (Fig. 3.19).

"Green recovery" measures should be adopted by ramping up investment in energy-efficiency technologies, battery and hydrogen solutions to reduce the city's dependence on fossil fuels, and boosting employment in renewable energy.

3.4.3 Non-CO_2 Emissions Should be Put Under Control List of Beijing During the 14th Five-Year-Plan Period

Methane is a potent greenhouse gas (with global warming potential). In Beijing, methane emissions mainly stem from waste discharges, which account for 70%; and landfill of solid waste makes up 84% of the total waste discharge.

Beijing's methane emission has reached a plateau since the 13th Five-Year Plan period, and is projected to decline as the city changes the way it handles solid waste.

Waste incineration does not produce methane emissions, and wastewater emissions represent approximately 26% of total methane emissions, of which 15% are from domestic sewage.

There are 38 waste disposal facilities in Beijing, including 10 for sanitary landfill, 11 for incineration and 9 for biochemical treatment. By 2015, about 50% of the city's garbage had been incinerated or biochemically disposed of. By the end of the 13th Five-Year Plan period, Beijing could handle 30,000 tons of household waste per day, which is estimated to reach 38,000 tons by the end of the 14th Five-Year Plan period.[37]

(1) Beijing will place CH_4 emissions under its control target of greenhouse gases emissions during the 14th Five-Year Plan period, so that such emissions will be no higher than 2020. To reduce landfill and increase the share of incineration, the following measures can be taken: advocate the benefit of garbage classification, heighten the awareness of citizens and teach the skills of classification; garbage truck operators should collect and sort out waste again before shipment to increase the calorie value of waste combustion, reduce harmful substances and improve resource utilization; and promote incineration of household waste.
(2) Scale up CO_2 refrigerant by promoting CO_2 refrigerant + waste heat recovery and utilization in the eight ice sports venues and large freezers of Beijing Winter Olympics to cut HFC gas emissions.

3.4.4 Synergy Between Low-Carbon Urban Transformation and Low-Carbon Winter Olympics in Boosting the Uptake of "Green Power"

The flexible DC grid pilot project in Zhangbei is a major source of renewable energy for Beijing Winter Olympics stadiums. It's the world's first four-end flexible DC grid that enables massive transmission of wind, solar and pumped storage energy, capable of delivering renewable energy from Zhangjiakou to Beijing and Yanqing Olympic Zone in a safe and efficient manner, facilitating 100% green electricity coverage of all venues. Meanwhile, the project provides a golden opportunity for tapping into renewable energy in Zhangjiakou, promoting its coordinated green development with Beijing.

Expand the import of green electricity. Ramp up the transmission of outside power to Beijing, so that with the aid of flexible DC grid, the capital can be "light up by the wind from Zhangjiakou". The increased power needs, in principle, should be met by green electricity. By 2025, the total import of green electricity is projected to hit 30 billion kilowatt-hours.

3.4.5 Maximize the Benefits of Carbon Pricing

Align carbon market in Beijing with that in China, and strive for more progress in the local pilot of carbon trading. Specific steps might include: draw up a more detailed list of traders from the building sector and update advanced value research; aircraft emissions from domestic flights should be incoporated; grant emission permits and verify the data quality of MRV.

Establish sound CCER trading centers and facilitate alignment with CORSIA of International Civil Aviation Organization (ICAO).

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Chapter 4
The Transition of China's Power System

Zongxiang Lu and Guiping Zhu

Abstract The energy systems of major countries are transitioning toward clean, low-carbon and intelligent solutions to combat climate change and environmental pollution. The goal to build a new electricity-centered energy supply infrastructure that progressively evolves toward an energy internet that integrates the exploitation, transmission, distribution and consumption of electricity has become a global consensus and object. It is expected that in the future, with continued innovations in power generation, transmission grid system, load and energy storage, and advances in information and communication technology, the structural pattern of the power system will undergo drastic changes. The future transition and development of the power system will be characterized by a high share of renewable energy in the grid, prevalent application of power electronic equipment, multi-energy complementarities and integrated energy utilization, and an intelligent grid network and energy internet with deeply integrated cyber-physical systems. This chapter is dedicated to examining the transition and development of the power system in the three main links of power supply, transmission grid and load. The trends of technological development are analyzed and suggestions on polices and measures to accelerate the transition are proposed.

Keywords Transition development · High share renewable energy (HSRE) · Multi-energy complementarities and integrated energy utilization · Deeply integrated cyber-physical system

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4.1 Background and Challenges of China's Power System Transition

4.1.1 Drivers of Power System Transition in the Era of Energy Revolution

Since the turn of the twenty-first century, the booming Chinese economy and subsequent soaring energy demands have produced mounting pressure of resource depletion and environmental degradation. In light of the challenges, President Xi Jinping called for an energy revolution in June 2014 in a bid to reduce energy consumption, increase energy supply, boost technology innovation and step up international cooperation. Pledging that China would "promote a revolution in energy production and consumption, and build an energy system that is clean, low-carbon, safe, and efficient", the *Report to the 19th Party Congress* delivered a clear path forward for the development and reform of China's energy sector.

The global call for environmental protection and sustainable development has also turned the spotlight on greenhouse gas emissions from the production and consumption of energy. On September 3, 2016, Standing Committee of China's National People's Congress adopted the proposal to review and ratify Paris Agreement. Under the framework of the agreement, China outlined a set of ambitious INDCs (Intended Nationally Determined Contributions): (1) cut CO_2 emissions per unit of GDP by 60–65% from the 2005 level by 2030; (2) increase non-fossil fuels in primary energy consumption to roughly 20% by 2030; (3) China's carbon dioxide emission will peak by around 2030 and the country will work hard to achieve the target earlier; (4) increase forest carbon stock by around 4.5 billion cubic meters from the level in 2005. The four targets articulate China's commitment to the world, and would underpin the country's transition in energy production and consumption. The proportion of non-fossil-fuel energy (mainly including renewable energy such as hydro, wind, and solar) in primary energy consumption represents a key metric in assessing energy transition.

To recapitulate, the primary goal of China's energy revolution is to gradually replace fossil fuels by renewables, increase the share of renewable and other clean energy sources in primary energy production and consumption, promote energy transition, and build a new-generation energy system that is clean, low-carbon, safe and efficient (Zhou et al. 2018). Since the power system is closely associated with the transmission and consumption of renewables, it's crucial for the fulfillment of core targets of energy transition. In this connection, the transition must be driven by technological development and innovation. The pursuit of clean development has brought greater diversity to the development of power systems where power supply, grid network, load and storage have witnessed profound changes. The deep integration of information and communication technologies (ICT) and physical systems has also emerged as a key trend. Meanwhile, the future blueprint of Energy Internet, an upgrade of smart grid, is being increasingly and widely embraced by the energy sector.

4.1.1.1 New Trends of Power Development Triggered by Global Energy Transition

The energy systems of major countries are transitioning toward clean, low-carbon and intelligent solutions to combat climate change and environmental pollution. The target to build *a renewable power-based* energy supply infrastructure that progressively evolves toward an energy internet that integrates exploitation, transmission, distribution and consumption of power has become a global consensus. It is expected that in the future, with continued innovations in power generation, grid system, load and energy storage, and advances in ICT, the structural pattern of the power system will undergo drastic changes.

A number of countries have rolled out plans for technological development in the energy sector in recent years, including the *Comprehensive Energy Strategy* of the US, the EU's *Energy Roadmap 2050*, the *National Energy and Environment Strategy for Technological Innovation Towards 2050* by Japan, South Korea's *Clean Energy Technology Roadmap* and China's *Energy Innovation Action Plan (2016–2030), Energy Technology Revolution Key Innovation Action Roadmap* and the *13th Five-year Plan on Scientific and Technological Innovation.* Technological innovation for the utilization of clean and low-carbon energy resources has become the "holy grail" of energy development in all countries, who have devised plans to underscore the centrality of renewables in energy supply of the future (Lu et al. 2017).

The international energy landscape has been dramatically adjusted. The fast-track development of unconventional oil and gas, spearheaded by the shale gas revolution in the US, had reshaped the traditional energy supply chain. The increasing maturity of renewable energy technologies has ushered in, quietly and assuredly, the era of energy transition and heralds a paradigm shift in the energy system. What's more, a new wave of Industrial Revolution, driven by big data, artificial intelligence and the Internet of Things, will propel the deep integration of the energy industry and the Internet. On the whole, four trends—decarbonization, electrification, decentralization and digitalization—are steering the transformation of energy and power sectors.

4.1.1.2 Transition of Domestic Power Sector in the Era of the Energy Revolution

At the historic intersection of the Energy Revolution and the Fourth Industrial Revolution, China remains firmly committed to the notion of green, low-carbon, clean and efficient sustainable energy development, and has actively enforced and revised its medium- and long-term energy technology strategies to cater to the evolving needs of ecological sustainability and national energy security.

The *Strategy of Energy Production and Consumption Revolution (2016–2030)* (hereinafter referred to as the Strategy), issued by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) on December 29, 2016, set out the medium- and long-term strategic goals of China's energy revolution. The Strategy stated that: (1) China aims to keep energy consumption within equivalent to 5 billion tons of standard coal by 2020, non-fossil energy will account for 15% of primary energy consumption, and natural gas will make up at least 10%; (2) China will keep energy consumption within equivalent to 6 billion tons of standard coal between 2021 and 2030, non-fossil energy will represent roughly 20% of primary energy consumption, natural gas 15%, and 50% of power generation will be derived from non-fossil sources; (3) by 2050, total energy consumption will be basically stable and non-fossil energy will contribute over 50%.

It can be seen that the rising share of non-fossil fuels in primary energy consumption and the ensuing energy transition hold the key to China's energy revolution. The goal of delivering 50% of the power through renewables by 2030 stated in the Strategy serves as a key benchmark for the future development of China's power system, and something that must be accommodated in developing the country's new-generation power system.

The share of non-fossil fuels in primary energy consumption is a core metric for China's energy transition. Electricity is a secondary energy source derived from the primary energy sources. Power generated from non-fossil fuels hit 1.5 trillion kWh in China in 2015. Given that the average amount of coal consumed for thermal power generation in the year stood at 315 g/kWh, total primary energy consumption for power generation would amount to 472.5 million tons of standard coal equivalent (tce), or 11% of the 4.3 billion tce consumed in the whole year, just 1 percentage point of the national share of non-fossil fuels in primary energy consumption (12%) in the same year. In 2016, power generated from non-fossil fuels grew to 1.7 trillion kWh. Given that the average amount of coal consumed for thermal power generation in the year stood at 312 g/kWh, primary energy consumption for power generation would total 530.4 million tce, or 12.3% of the 4.36 billion tce consumed in the whole year, which was also 1 percentage point short of the national share of non-fossil fuels in primary energy consumption (13.3%) in the same year. The conversion of nearly 90% of the non-fossil fuels into electricity has cemented the dominant position of power in the use of non-fossil fuels in primary energy consumption in China, spurred the production and consumption of the country's non-fossil energy, and invigorated the strategic transition of its energy system. Therefore, a marked increase in the share of power from non-fossil fuels and the formation of a non-fossil-centric power mix would underpin China's energy transition, and stand as a tangible testament to the country's power transition and the development of a new-generation power system.

The EU, the US and China have outlined their blueprint of 100%, 80% and 60% renewable power system respectively by 2050. The power system will undergo major shift under the new scheme. Randomly fluctuating solar and wind energy will constitute the bulk of power generation, baseload power plants will gradually bow out of the stage, and conventional thermal generation units will adopt a daily start-and-stop regime. In the meantime, gas-fired stations, pumped-storage hydro power plants and energy storage devices will be utilized to compensate for the random fluctuations of weather-driven renewable energy. Flexibility will be at the heart of the planning and operation of power systems.

The overriding trend at the source side is the shift toward a clean power supply. The booming development of renewable sources such as wind and solar (over 30% of local power generation), full development of hydropower, the re-positioning of thermal power for peak load shaving, and the steady development of nuclear power will contribute to a new and sufficiently clean power supply.

Power electronization of the grid is a rapidly accelerating trend. Long-distance transmission and on-site balanced power supply work in tandem as local conditions demand. Hybrid AC/DC grid is widely used. A range of new equipments in the distribution networks are emerging and technologies for DC distribution are being developed at a breakneck pace.

There is multiple uncertainty in terms of electric load. The emergence of distributed generations, electric vehicles, distributed energy storage and bidirectional load have brought out the interactive and dynamic nature of the entire power system comprised of power source, grid, load and storage. Uncertainty has become the core issue facing the planning and operation of power system.

4.1.2 Trends and Key Technologies of China's Power System Transition

4.1.2.1 The Trends of China's Power System Transition

The development of power systems in the past decade and, more specifically, the rapid adoption of wind and solar photovoltaic in electricity generation, the massive construction of UHV DC lines under the West-East Electricity Transmission Project, and the rise of distributed generations located on the consumers' side, multi-energy complementarities for integrated energy utilization and the energy internet exemplify the technological characteristics of the new-generation power system. A high share of renewables in overall power production, the prevailing application of power electronics, multi-energy complementarities for integrated energy utilization, a smart grid and energy internet featuring a high degree of cyber-physical integration are what distinguish the new-generation power system from its predecessors.

(1) **A high share of renewables in power generation**

In 2019, new installation of grid-connected wind power capacity reached 25.74 million kW, of which 23.76 million kW originated from onshore wind farms and 1.98 million kW from offshore wind farms. At the end of 2019, the nationwide cumulative installed capacity of wind power amounted to 210 million kW, including 204 million kW from onshore and 5.93 million kW offshore. Wind power accounted for 10.4% of total generation installation. In 2019, China's wind power production exceeded 400 billion kWh for the first time, reaching 405.7 billion kWh, or 5.5% of the country's total electricity generation. The country added 30.11 million kW of new PV capacity in 2019, a year-on-year decline of 31.6%. Newly installed centralized PV capacity slid to 17.91 million kW, down by 22.9% year-on-year while newly installed distributed PV capacity surged 41.3% to 12.2 million kW. Cumulative installed PV capacity reached 204.3 million kW, up 17.3% year-on-year. Cumulative installed centralized PV capacity grew 14.5% to 141.67 million kW and that of distributed PV rose 24.2% to 63.63 million kW.

With the massive centralized grid-connection of renewable power, the technical challenge, first and foremost, is adopting wind and solar power into a weak grid. The issue is particularly acute in northwest China, where the grid remains vulnerable in spite of the 750 kV AC and multiple DC transmission lines. The ability of the grid to absorb the amount of variable power that comes from renewables remains a big headache. Specifically, the problem can be broken down into two parts. The first concerns the impact of wind and solar variability on power system stability in weak grids. Through the coordinated control of renewable generation units, power stations and clusters of stations, along with grid control, such problems as voltage fluctuations, power frequency variations and poor power quality can be addressed. The second concerns the need for peak and frequency modulation of power system stemming from the volatile, intermittent and uncertain nature of wind and solar power, as well as wind and solar curtailment. Wind power generators saw its worst curtailment in China in 2016, which totalled 49.7 billion kWh or 20% of the total amount generated. The province of Gansu topped the list with a 43% curtailment, followed by Xinjiang's 38%. In the past few years, with the strengthening of government control over orderly planning and construction, the implementation of priority scheduling strategy for wind power and PV in the dispatching operation section, and the improvement of the technology of power forecasting and optimal operation by the wind farms and PV stations themselves, the expected goal of controlling the curtailment rate within 5% has been basically achieved.

Given the reality of grid in China, the following measures can be taken to reduce wind and solar power curtailment: (1) upgrade flexibility in power supply and storage. For instance, coal-fired power takes up 65% to 90% of the total output in north China, but the share of flexible resources such as pumped storage stations only made up somewhere between 0.5% and 1.2%. Flexibility in coal-fired power plants should be improved and energy storage stations should be developed to cope with wind and solar power curtailment; (2) encourage local consumption based on local conditions, including the placement of industries with high energy loads, district heating and surplus electricity to produce hydrogen and methane; (3) boost grid interconnectivity and complementarity between hydro, wind and solar power; (4) promote concentrated solar power (CSP); (5) build power transmission lines.

Apart from the above measures, new possibilities can be explored to address wind and solar curtailment as grids and power technology continue to evolve.

(2) Power electronization of the power system

The new-generation power system will be characterized by the proliferation of power electronics, the most important of which is the UHV transmission system that has flourished in recent years. China, the global test bed for UHV transmission lines, had built nine UHV AC and ten DC lines by June 2019 and is building another three UHV AC and one DC lines. The total length of operating UHV lines in the country amounted to 27,570 km, and the total transformation (conversion) capacity stood at 296.2 million kVA (kW). By the end of 2019, China's UHV lines had delivered more than 1.15 trillion kWh of electricity cumulatively, making tremendous contribution to stable power supply, clean energy development, environmental improvement and grid safety.

East and South China, the two major load centers where multiple DC transmission terminal stations are located, are the focus of the country's UHVDC construction project. Technical challenges of system operation, such as the dynamic reactive power support in handling the commutation failure to a receiving-end grid with multi-DC lines feeding, and stable and coordinated control of sending and receiving-end in AC-DC hybrid systems, require further research for solutions.

Furthermore, with intensified development of renewable energy in western China and growing demand for west-east power transmission, clean power in China's west will be produced through the complementarity across regions and river basins of diverse energy sources of hydro, wind and solar as well as from low-emissions coal plants with tremendous flexibility, and transmitted over long distances to load centers in east China, with renewables as the mainstay. The vision Zhou academician proposed to build a DC transmission grid on top of the existing west-to-east single-phase HVDC to supply energy from the west to the load centers in the east may very well become a reality (Zhou et al. 2013).

The demonstration project of four-terminal VSC-HVDC from Zhangbei to Beijing (see Fig. 4.1), which began construction at the tail end of 2017, will provide China with useful experiences for the construction of DC grids in the future.

On the other hand, with the development of renewable energy, a host of power electronic converters such as direct drive wind turbine converters, PV power plant and distributed PV inverters, non-hydro energy storage stations and distributed energy storage inverters, are now connected to the grid. In additional to centralized large wind and solar installations, more small-capacity, distributed wind and solar power systems are being implemented. At present, wind and solar power curtailment has hobbled the development of centralized wind and solar power in western China while distributed wind and solar generation has witnessed substantial growth in the central and eastern regions. Meanwhile, the ongoing poverty alleviation project by installation of solar PV panels in poor households has also dramatically increased the amount of power electronic equipment connected to the grid.

As a rising number of power electronic equipment of various types and voltage levels are connected to the grid, the increasing power electronization of China's power system will lead to a range of challenges in such areas as operation safety, system analysis and control, and simulation modeling and calculations. They include:

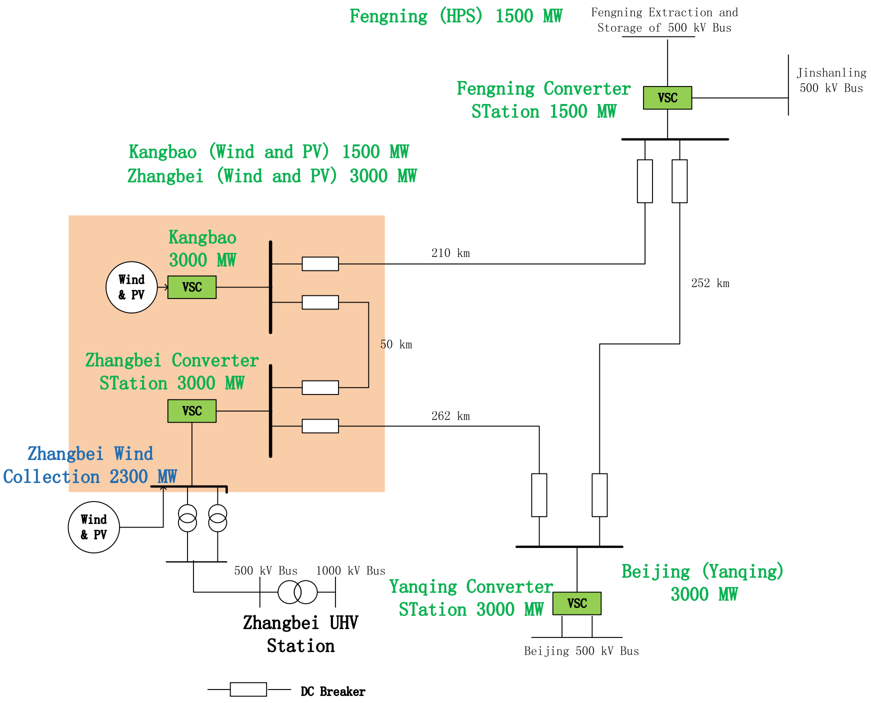


Fig. 4.1 Demonstration project of 4 terminal VSC-HVDC from Zhangbei to Beijing

1. Prevent large-scale power shift and cascading failures that can propagate across the AC-DC transmission systems as the result of a fault in the receiving-end of DC power transmission system.
2. The problem of voltage instability triggered by the restart following commutation failure in multi-feed DC receiving-end.
3. The issue of frequency fluctuation and instability due to reduced system inertia.
4. With an increasing number of power electronic devices such as for wind power solutions connected to the grid, broadband oscillations (1-kHz) are produced by the interactions among power electronics as well as between power electronics and the AC grid.

The analysis, simulation and control of subsynchronous or high-frequency oscillations sparked by the integration and interfacing of power electronics to the grid will become crucial matters. The above-mentioned problems have presented new challenges to existing grid simulation and system analysis. In the future, with more connection of sophisticated power electronic devices to the grid on a greater scale, it will be even more difficult to manage the complexity of the grid. Therefore, more work needs to be done in the research of grid characteristics, the development of modelling and simulation technology and control measures to ensure the safe and reliable operation of China's AC/DC hybrid power system.

(3) Integrated energy and power system with multi-energy complementarities

The new-generation power system has evolved along with China's energy transition. It will no longer be an isolated system of power production and consumption, but main part of the larger new-generation energy system of the country and an expansion and upgrade of the smart grid notion toward a comprehensive energy system. Such a system can be further subdivided into two types based on the reality of integrated energy utilization in China:

1. Source-end integrated energy system. The western region of China is blessed with an abundant supply of various forms of renewable energy resources, promising enormous potential for energy production. However, due to spacial limitations of power transmission and other technical constraints, the capacity of the West-East power transmission project has been held below 600 million kW. While local consumption of power should be maximized, a great amount of electrical energy must also be converted into other forms of energy for storage and transportation. Therefore, the establishment of a source-end integrated energy system in China's northwest is imperative. Such a system will allow for complementarities among hydro, wind, solar and clean coal to transmit power to the central and eastern parts of the country through a DC transmission grid; greater local consumption through heating, cooling, industrial consumption and other means; and production of hydrogen and methane by electrolysis for local consumption as well as for eastward transmission through natural gas pipelines.
2. Consumption-end integrated energy system. Serving primarily the eastern parts of China, the system aims to enhance energy efficiency and bring down total energy use. At present, thermal power generation remains the dominant source of electricity in China, with a thermodynamic efficiency of between 30 and 40%, calling for an integrated energy system to upgrade energy efficiency. The system is mainly comprised of a clean energy-based regional integrated energy system that caters to the diverse needs of users, distributed energy systems that directly interface with various types of end users under the active distribution network as well as a multitude of energy storage and renewable energy micro-grids. The combined cooling-heating-power (CCHP) system based on natural gas and clean power is shown in Fig. 4.2, and the user-oriented integrated energy system architecture is shown in Fig. 4.3.

(4) An intelligent power system and energy internet featuring deep cyber-physical integration

The pace of progress in the ICT industry has prompted gradual integration of various energy systems and Internet technologies to create an energy internet where information and energy interact at a level never seen before. If one examines the traditional power system through the lens of the Internet, one can see that the way the centralized and distributed power sources are connected to hundreds of millions of households through massive interconnected transmission and distribution networks is naturally characterized of networks. In fact, the end-users of traditional power systems have long enjoyed "plug-and-charge" without needing to know which power

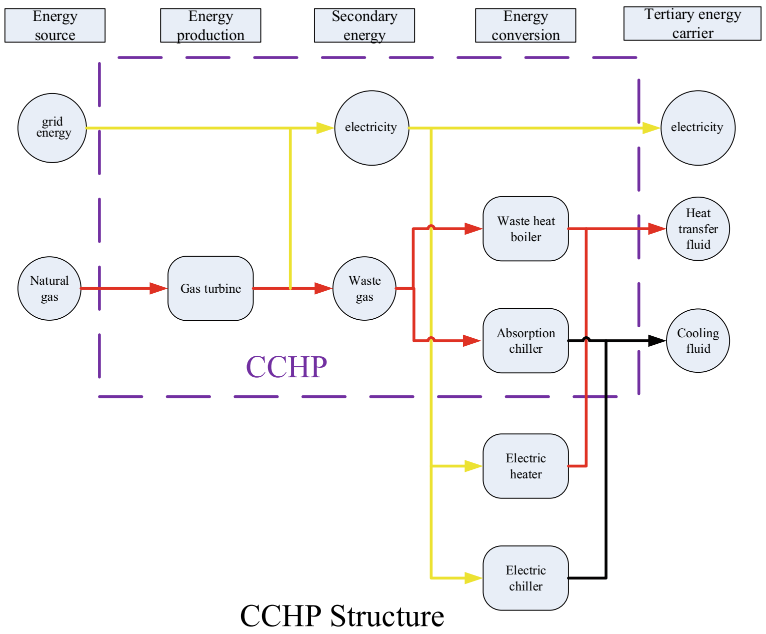


Fig. 4.2 Combined cooling heating and power system (CCHP)

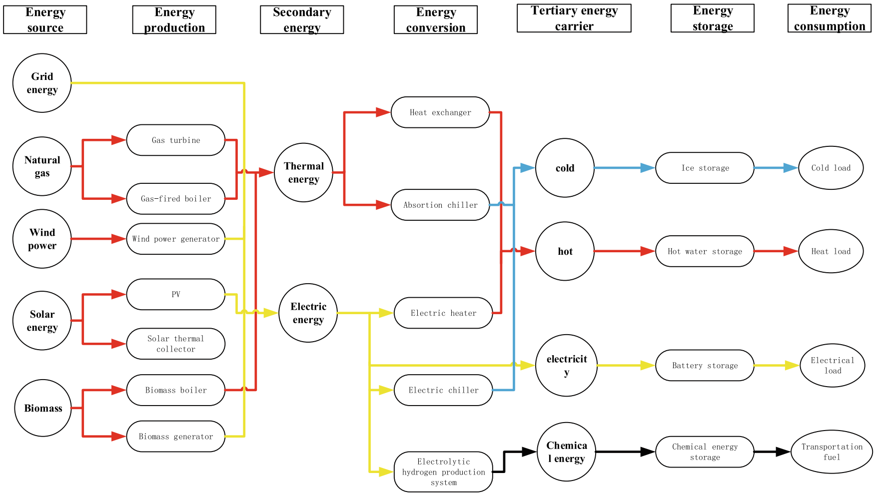


Fig. 4.3 User-oriented integrated energy system architecture

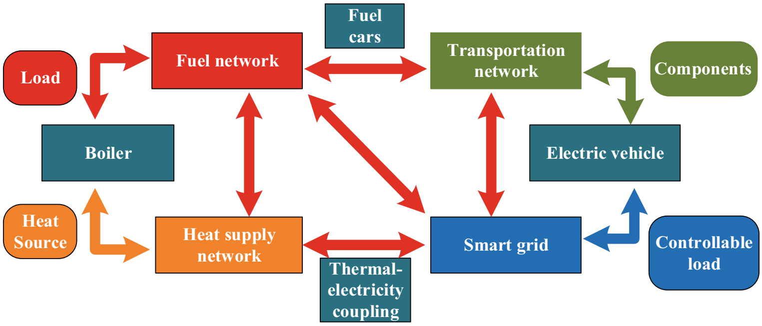


Fig. 4.4 Energy internet architecture

plant is supplying the electricity. The way electricity is consumed is typical of the open and shared nature of the Internet. On the other hand, an examination of the traditional power system through the lens of the Internet also reveals a lack of flexibility and storage options, ineffectiveness in integrating concentrated and distributed renewable power into the grid, inability to support multiple energy conversions or the mutual conversion and complementarities between various forms of primary and secondary energy sources, and bottlenecks to the improvement of integrated power efficiency and renewable energy utilization. The centralized and unified management, dispatching and control mechanisms of the traditional power system are not suited to large-scale distributed power generation, nor does it align with the trend of energy systems integration for efficient power utilization.

The energy internet formed through the interconnection of intelligent power systems with deep cyber-physical integration and multiple energy production and consumption networks including transportation, heating and fuel networks (see Fig. 4.4) on the basis of smart grid is characterized by the following three properties:

1. It's an energy network built around the core of power system featuring a variety of interconnected energy sources. Through the coordinated utilization of multiple energy sources and leveraging their complementarities, the diverse energy demands of end-users are met and integrated energy efficiency is significantly improved.
2. It's a cyber-physical system with the deep integration of the energy system and Internet technology. Internet-based thinking and technology are employed to transform traditional power systems. The pervasive application of big data, cloud computing and the Internet of Things can greatly enhance the flexibility, adaptability, intelligence, operational and management capabilities of power systems, upgrade the grid's ability to absorb volatile power generation from renewables, and facilitate energy transition.
3. It operates on a business model and service approach that centered around the users, provide them with a portfolio of convenient and interactive energy, power and information services. While meeting energy needs of users, it seeks to create

more value for users and boost the market-oriented development of the energy sector and related industries.

In conclusion, the further integration of traditional power system and Internet of information, the transformation of the traditional power system through Internet-based thinking and technology, and the building of an energy internet are instrumental to developing the new-generation energy system, and where the development of the new-generation power system is headed. In fact, the new-generation power system is at the very heart of the new-generation energy system. The concept and system architecture of the energy internet are highly compatible with the new-generation energy system. Power is at the kernel of energy internet services while the smart grid provides the key platform where the needs of consumers are met to the greatest extent.

4.1.2.2 The Main Drivers of the Transition of China's Power System

The transition and development of China's power system are primarily driven by three factors, namely communal drivers, market drivers and technical drivers, as shown in Figs. 4.5, 4.6 and 4.7.

Communal drivers are chiefly the product of strategic needs at the national level and can be divided into four overarching domains—modernization, resource and

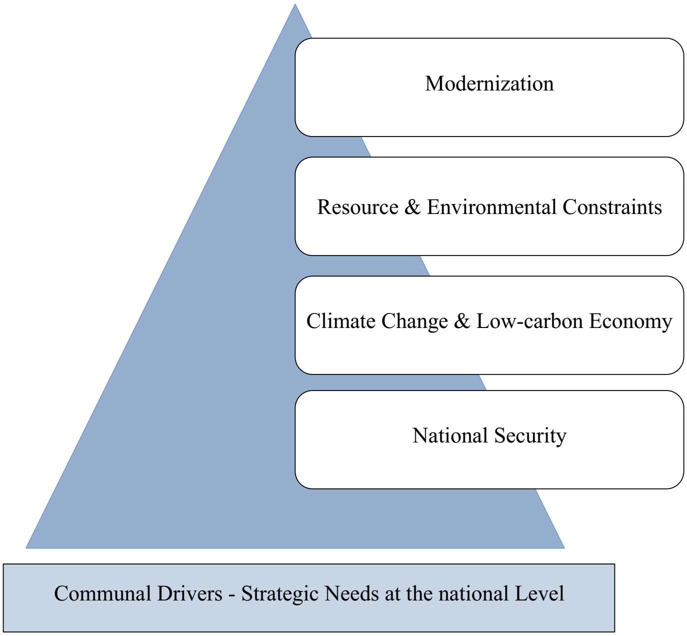


Fig. 4.5 Communal drivers of electrical power system evolution

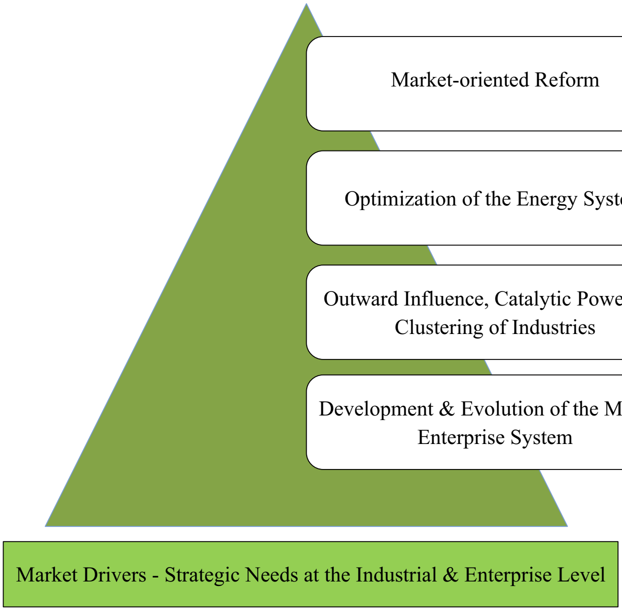


Fig. 4.6 Market drivers of electrical power system evolution

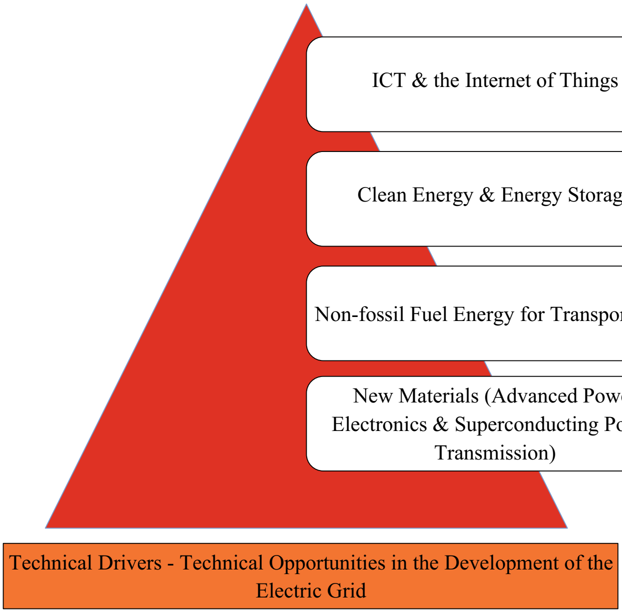


Fig. 4.7 Technical drivers of electrical power system evolution

environmental constraints, climate change and low-carbon economy, and national security.

The strategic needs of industries and enterprises are the linchpin of the market drivers, which can also be broken down into four domains, namely market-oriented reform, the optimization of the energy system, the outward influence, catalytic effect and clustering of industries, and development and evolution of the modern enterprise system.

The technical drivers are primarily derived from the technical challenges and opportunities facing the development of power systems. The current technological hotspots include ICT and the Internet of Things, clean energy and energy storage, non-fossil fuel energy for transportation and new materials (with the focus being on advanced power electronics, superconducting power transmission and etc.).

The various drivers of electric power system evolution differ in both the amount of force applied and the way in which change is exacted under different temporal and environmental contexts. The evolution occurs from the inside out when it is driven by technical factors. The changing of the guard between old and new technology and the improvement of key technical indicators result in a gradual and highly predictable form of evolution. On the contrary, changes prompted by external, communal drivers, which are forceful and radical in nature, may lead to a complete unpredictable reconstruction of the entire system. Market drivers straddle in between the two in terms of how they initiate change in the electric power system. On the one hand, market-oriented reforms contribute to restoring the qualities of electricity as a commodity and the optimal allocation of resources. On the other hand, the grid as a social infrastructure and public service is characterized as a natural monopoly and will not be entirely profit-driven.

4.1.2.3 Key Technologies for Promoting the Transition and Development of the Power System

The development of the power system moves in lockstep with technological progress. The following technologies may have disruptive impacts on the new-generation power system.

(1) Efficient and low-cost solar and wind power generation and grid-friendly technologies

The large-scale development and application of such technologies will displace the traditional methods of power generation, consign fossil energy-based power to the dungheap of history and revolutionize the production and consumption of energy. In fact, with the development of related technologies since 2000, the levelized cost of energy (LCOE) of large-scale terrestrial PV projects has dropped by 85% over the entire life cycle. In the meantime, according to the US Department of Energy (DOE), the LCOE of PV will be cut to 3 ¢/kWh by 2030. The planning and construction time for renewable energy projects is short, relative to other forms of energy such as thermal, hydro and nuclear power installations. The construction period for 50 MW wind power project is roughly several months while that for MW-level PV plants is less than half a year. Therefore, if significant cost reductions occured, the share of renewable energy capacity will grow rapidly.

(2) High-efficiency, low-cost and long-cycle life energy storage

The large-scale application of such technologies will revolutionize how traditional power systems operate, usher in a new form of power generation and distribution, and lay the foundation for the new-generation power system powered by a high percentage of or even 100% renewable energy. The average cost for lithium iron phosphate batteries stood at roughly 3000 yuan/kWh in 2015, and is expected to drop to just 1000 yuan/kWh in 2020. The energy storage cost of lithium ion batteries was close to 0.65 yuan/kWh in 2016, and is set to be reduced to 0.12 yuan/kWh in 2030. The notable reduction in the cost of energy storage solutions will overcome renewable variability. In addition, it is expected that by 2030, ultra-high density batteries such as lithium-air batteries will reach energy densities of 8–10 kWh/kg (calorific value of petrol 5.94 kWh/kg). Such ultra-high energy density storage technologies will transform the way electricity is generated, transmitted, distributed and consumed.

(3) Power electronics with higher reliability and lower losses

The uptake and application of such technologies will gradually displace the traditional AC-dominated transmission and distribution network and set the stage for a new system characterized by the coexistence of DC and AC/DC hybrid transmission and distribution. On the one hand, the development of Wide Band Gap power semiconductor devices such as SiC and GaN will drive HVDC transmission and DC grids to achieve greater capacity, efficiency and reliability. The HVDC circuit breakers based on WBG devices are also a main component of the DC power grid. On the other hand, the connection to the grid of a new generation of FACTS devices and power routers with greater power density and lower losses will assist in the construction of DC distribution networks. As power converters for microgrids, they will also bring revolutionary changes to low-voltage active distribution networks and microgrids.

(4) High-strength low-cost environment-friendly insulation and superconducting power transmission technology

The development and application of such technologies will transform traditional transmission lines and equipment. Among them, the development of insulation materials with high dielectric strength, high non-linearity, resistance to heat and cold and high voltage tracking resistance can improve the long-term safety of equipment, contribute to the miniaturization of electrical components, significantly enhance the performance of electrical devices and help achieve environmental sustainability. New superconductor technology will provide a brand-new low-loss, large-capacity, long-distance power transmission solution for the power grids of the future. Meanwhile, superconducting fault current limiters and superconducting magnetic energy storage systems will measurably improve the safety and reliability of power grid operations.

(5) A new generation of artificial intelligence

Built on the ubiquitous sensing and advanced ICT and with the Internet of Things, big data, cloud computing, deep learning and blockchain at the core, artificial intelligence is rapidly evolving with the potential to be applied in such fields as power system equipment management and system control, energy management and trading, and may reshape the traditional landscape to create a new future featuring automatic and autonomous processes, and lend a powerful hand in improving the safety, economy and reliability of the new-generation power system. For instance, the variability and uncertainty of solar power and the temporal and spatial uncertainties associated with EVs will introduce more variables into the equation. Traditional methods of analysis will meet a host of challenges in terms of scheduling, transaction and energy management, to which artificial intelligence will be able to provide new insights and solutions.

The development of these technologies will produce significant impacts on the future power system, how it operates and how transactions are conducted. Indeed, the development and application of these technologies are inextricably linked to market demand. So economics must be considered. Only technologies and equipment proven to be competitive in the market place will see broader application and continue to evolve down the path.

The development of the new-generation power system will be a long-term process. In this regard, new and meaningful technical trends may emerge during this process beyond the above-mentioned ones. Therefore, it's essential to keep abreast of potential innovation, continue to embrace new technologies and make due adjustments to the system in a timely manner.

4.2 Research on China's Power Generation Mix

4.2.1 The Evolution of China's Power Generation Mix

Since the founding of the People's Republic of China, especially in the four decades since the country embarked on reform and opening up, China has achieved remarkable social and economic success. In the meantime, the demand for electricity has risen exponentially, and total installed capacity has grown consistently over the years. In 1979, the Chinese mainland's total installed capacity amounted to a mere 63.02 million kW, and it more than quadrupled to 298.77 million kW in 1999. Total installed capacity scaled up to 2.01066 billion kW in 2019, a surge of more than 30-fold in the past four decades.

Figure 4.8 shows China's installed capacity in the years between 1979 and 2019. It can be seen that it has been growing year by year and the growth picked up pace notably after 2003. The accelerated growth was due to, on the one hand, a surge in the demand for electricity thanks to China's soaring GDP after 2003, and on the other hand, the reform of the power system in 2002, which split the State Power

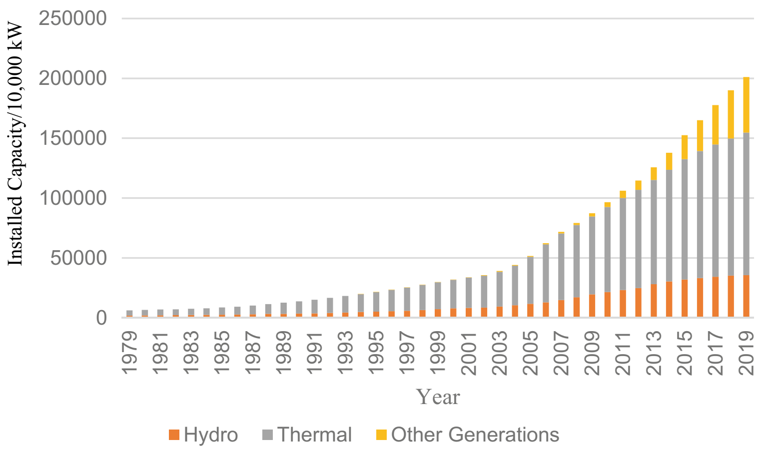


Fig. 4.8 Total installed capacity in the years between 1979 and 2019

Corp of China into five power production firms and two grid companies. The power production firms went on to expand and ramp up investments, which led to accelerated capacity installations.

China’s power generation mix has also been evolving and improving as installed capacity continued its breakneck growth. Figure 4.9 shows the share of multiple forms of power generation in total installed capacity from 1979 to 2019. For the first 30 years, data are presented in ten-year intervals, and for the past decade, data

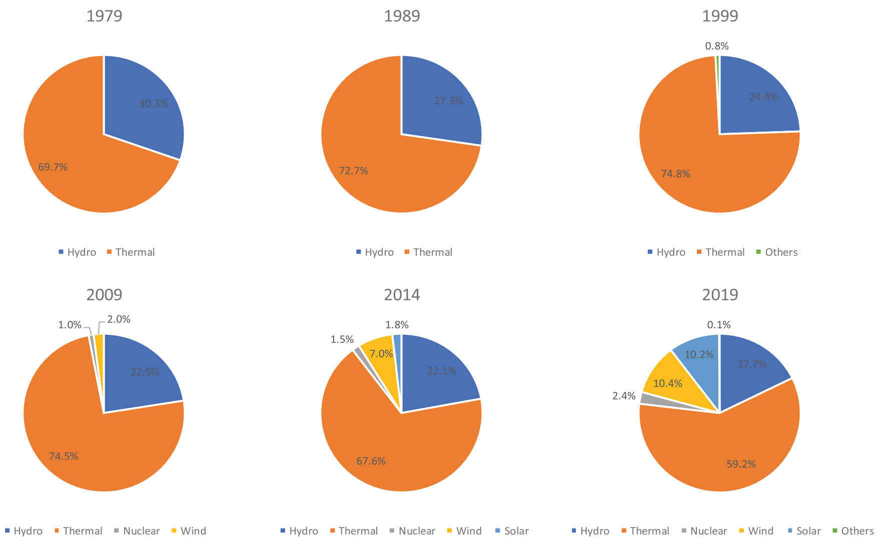


Fig. 4.9 The share of multiple forms of power generation in total installed capacity from 1979 to 2019

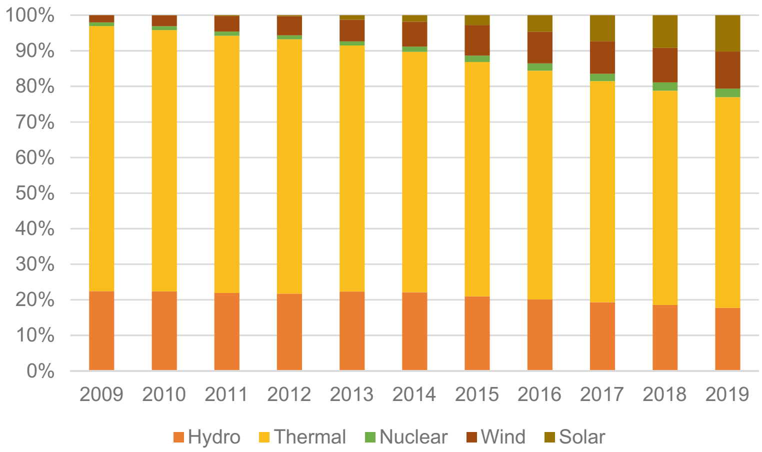


Fig. 4.10 The share of multiple forms of power generation in total installed capacity from 2009 to 2019

are illustrated in five-year intervals. Though thermal and hydro power sectors have witnessed a contraction in installed capacity as a share of total capacity in recent years, they still represent the bulk of China's power generation. In 2019, thermal, hydro, wind, solar, nuclear and other forms represented 59.2%, 17.7%, 10.4%, 10.2%, 2.4% and 0.1% of the total installed capacity, respectively.

Between 1979 and 1999, China's generation portfolio composed almost entirely of hydro and thermal. Beginning in 2009, the share of non-hydro renewable sources (mainly including wind and solar power) in the energy mix has risen sharply. In 2009, the proportion of solar in the energy mix stood at a negligible level, and the total installed capacity of nuclear and wind combined amounted to a mere 3%. Fast forward to 2019, the share of non-hydro renewable sources in the energy mix had soared to 23%.

Figure 4.10 shows the share of multiple forms of power generation in the total installed capacity between 2009 and 2019. It is evident from the data that the share of hydro and thermal in the total installed capacity has been on a steady decline. The decline of thermal power generation was particularly pronounced, though its predominance in the energy mix still holds. Nuclear, wind and solar power have grown to become important components of China's energy mix.

The landscape of power generation in China has shifted from thermal and hydro dependency toward a more diversified mix of resources including wind, solar and nuclear. In the meantime, the country is transitioning from high to lower-emissions sources of power generation. The improvement of China's energy mix has laid the groundwork for its low-carbon energy transition and sustainable development.

4.2.1.1 The Development of Thermal and Hydro Power in China

Figure 4.11 shows the installed capacity of thermal and hydro power and their shares in the total mix in the years between 1979 and 2019. The installed capacity of thermal and hydro power plants soared from 1.69 million and 0.16 million kW at the beginning of the founding of the PRC in 1949 to 1.19 billion and 356.4 million kW in 2019. A closer examination of the trends reveals that, between 1979 and 2003, growth in the total installed capacity of hydro and thermal power was relatively flat, and that thermal installations first picked up pace notably between 2003 and 2015, then tapered off after 2015. A look at their respective shares in the total installed capacity shows that the weight of hydro power has been on a consistent decline from 30.3% in 1979 to 17.7% in 2019; the proportion of thermal power capacity first grew gradually from 69.7% in 1979 to 77.6% in 2006, and took a plunge afterwards to just 59.2% in 2019.

Here are the main drivers behind this trajectory of development: the development of renewable energy sources such as wind and solar had yet to be brought to scale before 2006, and hydro and thermal power remained the largest sources of China's energy mix. As the demand for electricity rose steadily, thermal power installations took off, resulting in a rising share of thermal power and a decline in the share of hydro. After 2006, the installation of renewable energy capacity such as wind and solar was ramped up dramatically, and the share of hydro and nuclear in the energy mix dropped correspondingly. The fall in the share of thermal power in the overall portfolio was particularly steep under the influence of macro policies that supported energy saving and emissions reduction.

Though coal-fired power will remain the dominant source of electricity in China for a long time to come, the installed capacity of coal power and its share in the total mix are expected to go on a downward trajectory under the dual pressures of energy

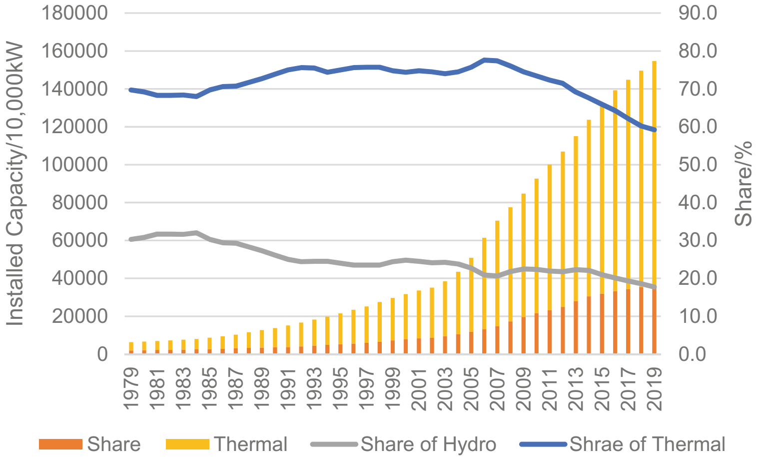


Fig. 4.11 The installed capacity of thermal and hydro power and their shares in the total mix

security and environmental protection. Clean coal technologies will be increasingly valued and deployed. Peak shaving technologies for thermal power plants also lay the technical groundwork for improving the integration of renewable energy assets within power grids.

4.2.1.2 The Development of Nuclear Power in China

In December 1991, China's first commercial nuclear power plant (Qinshan 1) was connected to the grid, and by December 2019, the Chinese mainland had 45 nuclear power units in operation in 16 nuclear plants. The installed capacity of nuclear power stands at 48.74 million kW, accounting for 2.4% of the total installed capacity. In 2019, the country's nuclear power plants produced 348.7 billion kWh, or 4.8% of the total electrical output.

The installed capacity of nuclear power and its annual growth on the Chinese mainland between 2009 and 2019 are shown in Fig. 4.12. With the exception of 2012, the country's nuclear capacity expanded during all other years. However, there have been marked fluctuations in the growth. Nuclear power now plays a noticeable role in the overall energy mix, though its share in the total installed capacity remains minor. Between 2009 and 2019, the share of nuclear power in the total installed capacity edged up from 1.0 to 2.4%. In the wake of the Fukushima nuclear accident in 2011, China took a much more cautious stance to the approval of nuclear power projects. In December 2012, the National Nuclear Safety Administration approved the construction of the third and fourth units (Phase II) for the Tianwan Nuclear Power Plant. No new approvals were granted in 2013 and 2014. In 2015, a total of eight nuclear power units were approved. No conventional nuclear power projects were approved in the subsequent three years (Xu 2018). In October 2019, construction

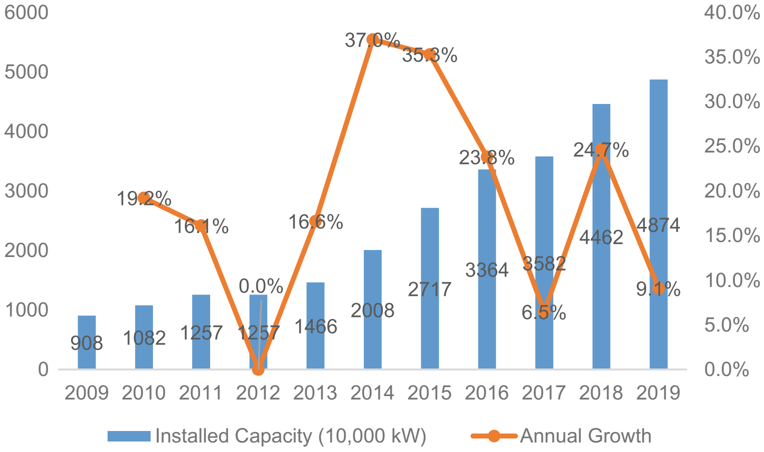


Fig. 4.12 Nuclear electricity generating capacity on the Chinese Mainland 2009–2019

licenses were issued for units 1 and 2 of the Zhangzhou nuclear power plant in China's Fujian province.

In the 13th Five Year Plan on electric power development issued by the National Development and Reform Commission and the National Energy Administration in 2016, it was proposed that China would have 58 million kW of installed nuclear power by 2020 (The 13th Five-Year Plan for Electric Power Development 2016). However, actual growth fell short of the government's target. By the end of 2019, the installed nuclear power generation capacity only rose to 48.74 million kW from 33.64 million kW in 2016. In February 2019, the China Electricity Council (hereinafter referred to as CEC) advocated for revising the 2020 target down to 53 million kW (Mid-Term Evaluation and Optimization of the 13th Five-Year Plan for Electric Power 2019).

Nuclear power plants provide a stable power generation with long utilization time. Nuclear is clean and zero-emission compared with thermal power, not affected by seasonality compared with hydro, and free from natural conditional such as wind and solar power. Nuclear energy development holds enormous potential in China. However, technological upgrading and the safety of the facilities will be the highest priority in the development of nuclear power.

4.2.1.3 The Development of Wind Power in China

The first wind farms sprouted in the 1980s in China, but it was not until 2005 that wind power began to take off. The support of government policies, which drove a massive inflow of capital into the sector, fueled explosive growth in the installed capacity of wind power in China in the following decade. In 2008, the total installed capacity of wind power stood at 8.39 million kW, accounting for a mere 1.1% of the country's total installed capacity. In total, wind energy generated 13.1 billion kWh, or 0.4% of the country's total power generation. China's installed capacity of wind power had topped 210 million kW by the end of 2019, making up 10.4% of the country's power capacity. Wind energy produced 405.7 billion kWh, representing 5.5% of the country's power production in the year. Wind power has become an important part of China power supply mix.

The installed capacity of wind power between 2009 and 2019 and its share in the total mix are shown in Fig. 4.13. Figure 4.14 shows the capacity added each year and the rate of growth. It is evident from the data that since 2009, though the amount of newly installed capacity varied from year to year, a high level of growth was maintained throughout. The average annual increase in the installed capacity of wind power exceeded 15 million kW, and its share in the total mix has also witnessed a steady rise.

It is worth noting that although the installed capacity of wind power was seeing explosive growth, that did not translate into commensurate increases in the share of wind power in the total amount of electricity production. On the one hand, average utilization times of thermal, hydro and nuclear power plants are much longer than wind farms due to the unpredictable nature of wind energy. On the other, a significant

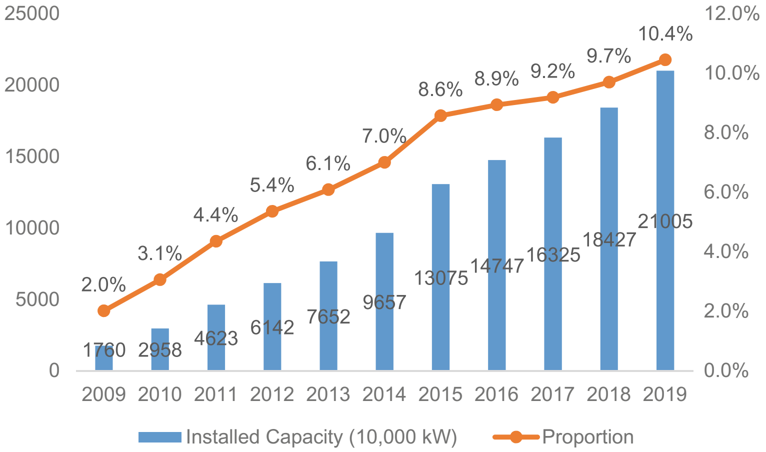


Fig. 4.13 Installed capacity of wind power between 2009 and 2019 and its share in the total mix

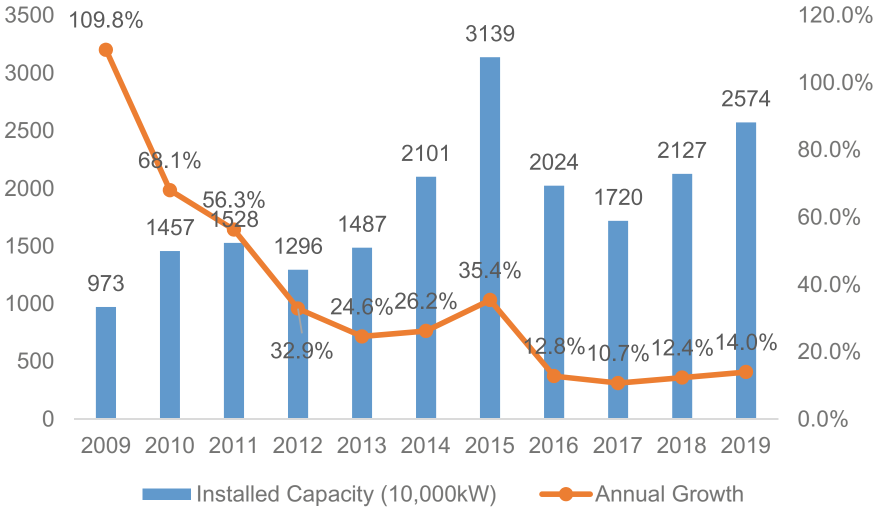


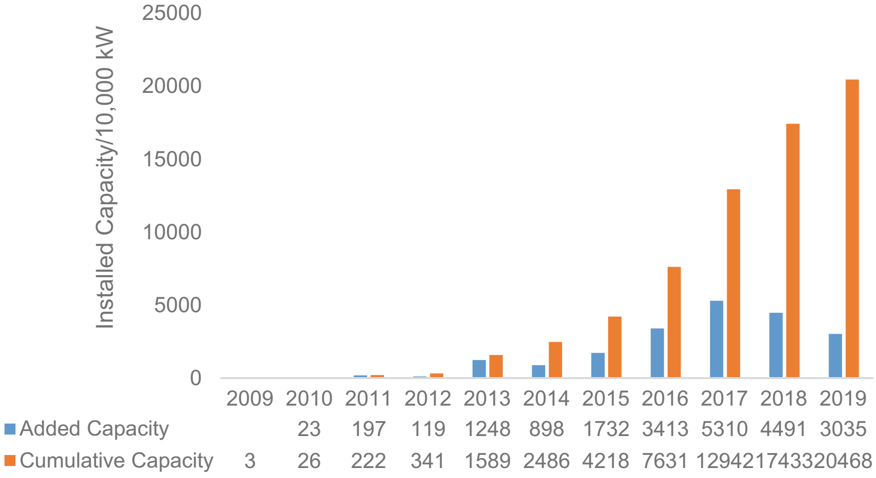
Fig. 4.14 Capacity added each year between 2009 and 2019 and the rate of growth

amount of wind curtailment occurs due to a number of factors. Wind power curtailment refers to the shutdown of wind power generator under normal conditions due to grids with insufficient capacity, unstable wind conditions, construction mismatch of wind farm and power grid, and so on. Wind power curtailment has been effectively alleviated in the past two years through such measures as grid optimization, deep peak regulation by thermal power units and wind-powered heating. Conditions were the most severe during 2015 and 2016. In 2015, up to 33.9 billion kWh of wind electricity failed to connect to the grid, and the average wind power curtailment rate stood at 15%. In 2016, wind electricity losses approached 49.7 billion kWh, at a curtailment rate of 17.1%. After several years of efforts, the total curtailed electricity from wind nationwide dropped to 16.9 billion kWh in 2019, at a curtailment rate of just 4%.

4.2.1.4 The Development of Solar Power in China

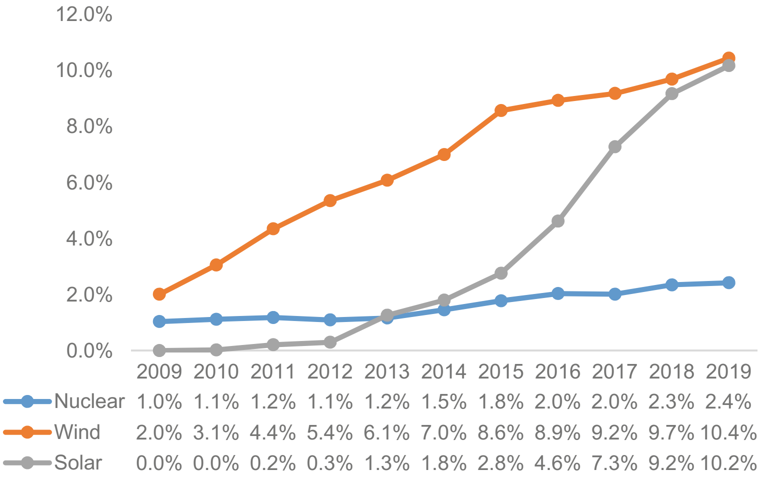
Photovoltaic and solar thermal power are the two established solar power technologies. Currently, PV dominates China's solar power industry. Figure 4.15 shows the cumulative and newly installed capacity of solar power in China between 2009 and 2019. Figure 4.16 illustrates the respective shares of nuclear, wind and solar in the total installed capacity in the same time span. It can be seen that in spite of the country's late start, solar power generation has grown enormously in China. By the end of 2019, the installed capacity of solar power had risen to rival that of wind power. Solar power has become an important part of the energy portfolio of China.

In 2016, China's installed capacity of solar power reached 42.18 million kW, and electricity produced from solar hit 39.5 billion kWh. China overtook Germany in both indicators to become the world's largest and fastest-growing solar energy market. In 2019, the total installed capacity of solar power in China stood at 204.68 million kW, generating 223.8 billion kWh of electricity. The share of solar power in the total installed capacity amounted to 10.4% in 2019, comparable to that of wind power (10.4%). The installed capacity of solar has pulled far ahead of nuclear and is edging closer to that of wind power. The share of both wind and solar in the total installed capacity topped 10% for the first time.



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
■ Added Capacity		23	197	119	1248	898	1732	3413	5310	4491	3035
■ Cumulative Capacity	3	26	222	341	1589	2486	4218	7631	12942	17433	20468

Fig. 4.15 Cumulative and newly installed capacity of solar power in China between 2009 and 2019



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Nuclear	1.0%	1.1%	1.2%	1.1%	1.2%	1.5%	1.8%	2.0%	2.0%	2.3%	2.4%
Wind	2.0%	3.1%	4.4%	5.4%	6.1%	7.0%	8.6%	8.9%	9.2%	9.7%	10.4%
Solar	0.0%	0.0%	0.2%	0.3%	1.3%	1.8%	2.8%	4.6%	7.3%	9.2%	10.2%

Fig. 4.16 The respective shares of nuclear, wind and solar in the total installed capacity between 2009 and 2019

Similar to wind power, curtailment is also a cause for concern for solar power generation. Totally speaking, solar fares better than wind in this regard, and its curtailment has been reduced significantly in recent years. In 2019, some 4.6 billion kWh of solar power were curtailed nationwide, at a curtailment rate of just 2%.

4.2.2 The Distribution of Various Energy Resources in China

4.2.2.1 The Distribution of Hydro Power Resources

China posses the world's greatest hydropower resources with a theoretical potential of 680 million kW, of which an estimated 540 million kW is exploitable. The enormous hydropower resources are distributed unevenly across the country, and mismatched the level of regional economic development. The vast majority are concentrated in relatively economically stagnant regions such as the west and southwest. Sichuan, Chongqing, Yunnan, Guizhou and Tibet together represent nearly two-thirds of the country's total hydropower resources. However, hydro resources are scare in the more economically prosperous central and eastern regions where the demand for electricity is the highest. This mismatch of power supply and demand has had a profound impact on the development of regional power grids. Table 4.1 gives an overview of the distribution of hydropower resources in China (Review Results of Hydraulic Resources in People's Republic of China 2003).

China has built 13 large-scale hydropower bases, which are principally located along the Jinsha River, Yalong River, Lancang River, Dadu River, and the upper reaches of the Yangtze River, as shown in Table 4.2 (Liu et al. 2016). Among them

Table 4.1 The distribution of hydro resources in China

Region	Technically exploitable hydro resources	
	Number of plants	Installed capacity (10,000 kW)
Yangtze River basin	5748	25,627.3
Yellow River basin	535	3734.3
Pearl River basin	1759	3129.1
Haihe River basin	295	203.0
Huaihe River basin	185	65.6
Northeast China	644	1682.1
Southeast Coast	257	1907.5
Southwest China	609	7501.5
Yarlung Tsangpo and other river basins	243	8466.4
The Hinterland and Xinjiang	712	1847.2
Total	13,286	54,164

Table 4.2 13 large-scale hydropower bases in China

Region	Installed capacity (10,000 kW)
Jinsha River	4789
Yalong River	1940
Dadu River	1805
Wu River	867
Upper Course of the Yangtze	2831
Hongshui River	1312
Mainstream of the Lancang	2137
Upper reaches of the Yellow River	1415
Northern mainstream of the middle reaches of the Yellow River	609
Xiangxi Tujia and Miao Autonomous Prefecture	791
Fujian, Zhejiang and Jiangxi	1416
Northeast China	1131
Nujiang hydropower base	2132
Total	23,197

Table 4.3 9 mega coal power bases in China

Region	(Planned) installed capacity (10,000 kW)
Xilingol	1588
Ordos	3858
Northern, Central and Eastern Shanxi	9200
Northern Shaanxi	4200
Hami	4000
Zhundong	1320
Ningdong	1600
Total	25,766

are the Three Gorges Dam—the world's biggest hydroelectric power facility with an installed capacity of 22.5 million kW, Xiluodu Hydropower Station with an installed capacity of 12.6 million kW and Baihetan Hydropower Station with an installed capacity of 12 million kW.

4.2.2.2 Distribution of Thermal Power Plants in China

Thermal power plants can be powered by coal, gas and oil. The fact that China is rich in coal, but poor in other forms of energy resources such as gas dictates that coal-fired power plants have been the dominant source of electricity in the country. China's coal-fired power capacity stood at 1.00845 billion kW at the end of 2018, accounting for 88.1% of the total installed thermal power capacity. The *Energy Development Strategy Action Plan (2014–2020)* released by the State Council in June 2014 called for utilizing the most cutting-edge energy-saving, water-saving and environmentally-friendly power generation technology to facilitate the building of 9 10 million-kW-plus mega coal power bases in Xilingol, Ordos, northern Shanxi, central Shanxi, eastern Shanxi, northern Shaanxi, Hami, Zhundong and Ningdong. The 9 coal power bases are listed in Table 4.3.

As can be seen from Table 4.3, these nine large-scale coal power bases are situated far from the load centers in central and eastern China. Consequently, the UHV power grid has become the premier choice for connecting the mega coal power bases to the load centers.

4.2.2.3 Distribution of Nuclear Power Capacity in China

The vast amounts of water are demanded by nuclear power plant for cooling, therefore using seawater as a cooling source is an advantage of nuclear power plants usually built in coastal area. All nuclear power plants in operation on the Chinese mainland are located in the coastal province such as Liaoning, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi and Hainan. The location and installed capacity of each nuclear power plant are shown in Table 4.4 (by October 22, 2019). It can be seen that China's nuclear power plants are sited more closely to the load centers. However, due to the relatively small total installed capacity, the nuclear power plants are still far from meeting the demand for electricity in these regions, a large share of which have to be transmitted through the power grid over long distance.

Table 4.4 Distribution of nuclear power plants on the Chinese Mainland

Power station	Location	Number of reactors	Installed capacity (10,000 kW)
Qinshan nuclear power plant	Haiyan County, Zhejiang	1	33.0
Daya Bay nuclear power plant	Shenzhen, Guangdong Province	2	196.8
Qinshan Phase II	Haiyan County, Zhejiang	4	262.0
Ling Ao nuclear power plant	Shenzhen, Guangdong	4	415.2
Qinshan Phase III	Haiyan County, Zhejiang	2	145.6
Tianwan nuclear power plant	Lianyungang, Jiangsu	4	437.2
Hongyanhe nuclear power plant	Wafangdian, Liaoning	4	447.2
Ningde nuclear power plant	Fuding, Fujian	4	435.6
Fuqing nuclear power plant	Fuqing, Fujian	4	435.6
Yangjiang nuclear power plant	Yangjiang, Guangdong	6	651.6
Fangjiashan nuclear power plant	Haiyan County, Zhejiang	2	217.8
Sanmen nuclear power plant	Taizhou, Zhejiang	2	250.0
Haiyang nuclear power plant	Haiyang, Shandong	2	250.0
Taishan nuclear power plant	Taishan, Guangdong	2	350.0
Changjiang nuclear power plant	Changjiang, Hainan	2	130.0
Fangchenggang nuclear power plant	Fangchenggang, Guangxi	2	217.2

The development of inland nuclear power plants has long been part of discussions and research efforts in China. Three inland nuclear power plants—Hunan's Taohuajiang power station, Hubei's Xianning Dafan power station, and Jiangxi's Pengze power station—were already approved prior to the Fukushima incident. However, the incident prompted China to halt all plans for constructing inland nuclear power projects. In recent years, the construction of inland nuclear power stations has re-entered the discussion. China's 13th Five-Year Plan on the development of energy called for "research and preparations for the construction of inland nuclear power plants".

4.2.2.4 Distribution of Wind Power in China

Unlike thermal and nuclear power, wind power output is greatly affected by a host of geographical and environmental factors. China's wind energy resources are mainly concentrated in the northeast, north, northwest and along the coast, which are also home to the vast majority of the country's wind power bases. In 2019, the top three provinces by cumulative wind capacity were Inner Mongolia (30.07 million kW), Xinjiang (19.56 million kW), and Hebei (16.39 million kW). Other provinces topping the 10 million mark included Shandong (13.54 million kW), Gansu (12.97 million kW), Shanxi (12.51 million kW), Ningxia (11.16 million kW) and Jiangsu (10.41 million kW).

In 2019, the regions with wind curtailment rates exceeding 5% included Xinjiang (14%, 6.61 billion kWh curtailed), Gansu (7.6%, 1.88 billion kWh curtailed) and Inner Mongolia (7.1%, 5.12 billion kWh curtailed). The three regions curtailed a combined 13.6 billion kWh of electricity generated from wind farms, or 81% of the country's total curtailment. The common denominator shared by these three regions is an abundant supply of wind energy, a sparse population, relatively low demand for electricity locally and lack of transmission capacity to export excess electricity elsewhere. To tackle wind curtailment, it is necessary to improve the power grid's capacity for transmitting wind power outward and for the coordinated generation, transmission and consumption of electricity across regions. In addition, local consumption of electricity should be bolstered through industrial transformation and upgrading, industrial transfer from the eastern regions, and the development of a number of energy-intensive industries such as hydrogen production by electrolysis and smelting. Low-cost wind power generated locally should be made full use of to reduce product cost and enhance their competitiveness.

4.2.2.5 Distribution of Solar Power in China

The total installed capacity of solar power in China reached 204.68 million kW at the end of 2019, 99.8% of which were from photovoltaic solar panels. In 2019, a total of 30.11 million kW of new PV capacity were added nationwide. 28.5% of the new capacity or 8.58 million kW were installed in northern China; 5.1% or 1.53 million kW in the northeastern region; 17.5% or 5.31 million kW in east China; 11.6% or 3.48 million kW in central China; 21.6% or 6.49 million kW in the northwestern region; and 15.7% or 4.72 million kW in southern China.

In 2019, the installed capacity of PV is mainly found in Xinjiang, Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Hebei, Henan, Shandong, Jiangsu, Anhui and Zhejiang, where the PV capacity has either exceeded or is approaching 10 million KW. Among them, Shandong (16.19 million kW), Jiangsu (14.86 million kW), and Hebei (14.74 million kW) topped the chart.

In 2019, solar power generation by photovoltaics nationwide totalled 224.3 billion kWh, up 26.3% year-on-year. The average number of hours of utilization of PV systems stood at 1169 h, an increase of 54 h year-on-year. The national solar curtailment rate fell by 1 percentage point to 2%, tallying to a total of 4.6 billion kWh of electricity curtailed. A closer examination of the various regions reveals that the challenge of curtailment is most acute in the northwestern region, which accounted for 87% of nationwide curtailment in 2019 in spite of a 2.3 percentage point drop in curtailment to 5.9%. The rate of curtailment in north, northeast and south China stood at 0.8%, 0.4%, and 0.2%, respectively. No solar curtailment occurred in central and east China. Parsing the data further at the provincial level, the curtailment rate in Tibet, Xinjiang and Gansu declined 19.5%, 8.2%, and 5.6% year-on-year to 24.1%, 7.4%, and 4.0%, respectively. Due to such factors as a notable increase in solar installations and a drop in load, Qinghai saw its curtailment rate rise to 7.2%, up 2.5% year-on-year.

Photothermal power generation is also called solar thermal power (STP) generation. Solar thermal power plants are generally composed of three subsystems: solar heat collection, heat storage and power generation. Heat storage gives STP systems the advantages of stable output and adjustability compared to PV power generation. In addition, the heat storage component can be integrated with other circulation systems to improve energy efficiency (Du et al. 2016).

Despite the clear advantages of STP, China remains at the very early stage in terms of the full-scale development of STP due to technology and cost barriers. The conditions for building STP plants are rather demanding: strong and direct solar radiation, a large amount of water and land as well as a flat landscape. Therefore, current STP plants in China are primarily concentrated in the northwestern and northern regions where the conditions are suitable. On September 13, 2016, the National Energy Administration issued a notice on the construction of solar thermal power generation demonstration projects, which contained a shortlist of 20 demo STP projects with a total installed capacity of 1.349 million kW to be built in Qinghai, Gansu, Hebei, Inner Mongolia and Xinjiang.

In summary, the curtailment of power generated from renewable facilities, mainly wind and solar, is most prominent in northwest China. The reasons are three-fold. First of all, renewables by their very nature are intermittent and volatile, and the power grids do not have sufficient capacity to adequately peak shave. Second, there is a mismatch between power generation installations and the construction of infrastructure for the outward transmission of renewable energy. Third, there are weaknesses in the power grid, and some regions are hobbled by grid constraints.

4.2.3 The Current Development of Distributed Renewable Power

The thermal, hydro, nuclear, wind and PV power generation discussed above are all large-capacity or centralized. Their output is connected to the high-voltage transmission grid via transformers, and then delivered over long distances to load centers. Distributed generation (DG) or decentralized generation, on the contrary, is directly either connected to the distribution network or designed to meet an end user's on-site electricity needs. DG capacity usually less than 10–30 MW. Currently, distributed renewable power sources in China mainly include small hydropower, distributed wind power and distributed photovoltaic power generation.

Small hydropower is a necessary supplement to large power grids. It helps to realign the mismatch between the supply and demand of electricity in the rural areas, stimulate growth in the rural economy, and accelerate the pace of rural electrification. The development of small hydropower projects is not only pertinent to the issues of energy and livelihood, but also key part of the country's poverty alleviation project. It is of enormous significance to the eradication of poverty in China's remote and underdeveloped rural areas. The current construction of small hydropower projects in rural China, besides having green development and poverty alleviation as its two overarching priorities, is ultimately aimed at aiding in the revitalization of rural communities and improvement of river ecology.

According to the *Annual Report on Rural Water Conservancy and Hydropower Work in 2018* released by the Ministry of Water Resources, 194 new hydropower stations were built in the rural areas in 2018, adding a total of 1.643 million kW in installed capacity, or 18.3% of the total newly installed hydropower capacity in the country. The vast majority of the installations were in southwest China. There were 46,515 hydropower stations across rural China at the end of 2018, with installed capacity of 80.435 million kW, which amounted to 22.8% of the total installed capacity of hydropower or 4.2% of total installed power capacity nationwide. Small rural hydropower plants are predominately concentrated in Yunan, Guizhou, Sichuan, Hubei, Hunan and Zhejiang. Their distribution is shown in Fig. 4.17.

According to the *Annual Report on Rural Hydropower in 2018* published by the Ministry of Water Resources, rural hydropower stations provided 214.95 billion kWh of electricity into the grid, with around 3.81 billion kWh supplied to nearby communities. 1519 counties across rural China were equipped with hydropower facilities at the end of 2018, the vast majority of which were found in southwest, central and southern parts of the country. Sichuan topped the list with 162, followed by Yunnan with 116 and Hunan with 96 small rural hydropower plants. The installed capacity of rural hydropower and the amount of electricity generated made up 62.8% and 43.8% respectively of China's total hydropower potential in rural areas. Provinces with higher utilization rates are chiefly concentrated in central and east China and southeastern regions along the coast, while rural hydropower still holds enormous untapped potential in southwest China where hydropower resources are more abundant and economic development has been relatively stunted. With the continuous

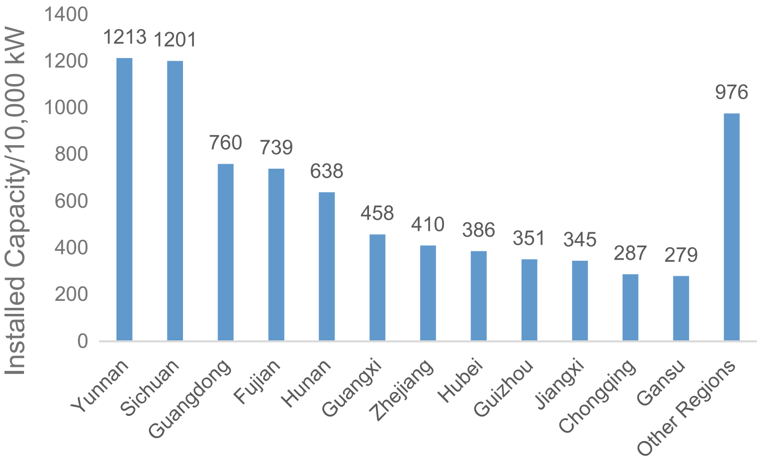


Fig. 4.17 Rural hydropower installed capacity by region at the end of 2018

construction of small hydropower projects in rural areas, they may very well become the leading source of power for rural communities and remote mountainous areas across the country.

The scale of distributed wind power remains limited in China. A growing number of provinces have announced plans for the development of decentralized wind power in recent years. Table 4.5 shows the regions with a planned distributed wind power capacity exceeding 1 million kW.

Currently, the most popular application of PV systems is rooftop photovoltaic installation. In 2019, 12.2 million kW of distributed PV capacity were installed nationwide, accounting for 40.5% of newly installed PV capacity and 11% of newly electricity. The cumulative installed capacity of distributed PV stood at 62.63 million kW at the end of 2019, a year-on-year increase of 24.2%. Distributed PV capacity represented 30.5% of all PV capacity and 3.1% of total installed power capacity. Topping the chart in terms of distributed PV capacity were Shandong (9.42 million kW), Zhejiang (9.42 million kW), and Jiangsu (6.56 million kW).

Table 4.5 Regions with a planned distributed wind power capacity exceeding 1 million kW

Region	Date of announcement	Planned capacity (10,000 kW)	Construction period
Henan	August 2019	453.7	"13th Five-Year Plan" period
Inner Mongolia	July 2019	122.0	2019–2020
Hubei	June 2019	113.5	2019
Hebei	January 2018	701.2	2018–2025
Guizhou	April 2013	120.0	2013–2020

Distributed renewable energy systems entail shorter construction period, lower infrastructure investments and present less impact on the environment and ecological system than their centralized counterparts. Electricity generated by distributed renewables prefers to be consumed on site, and any surplus is exported to the grid. The adaptive, clean, efficient, distributed and localized nature of distributed generation supports, on the one hand, the replacement or reduction of fossil fuel use through tapping into local resources, and on the other hand, the addressing or alleviation of the problem of power shortages in certain areas. In addition, distributed energy systems are located close to the end-user, thus entailing less complicated electric equipment and resulting in less transmission losses.

Although distributed renewable power generation remains supplementary to the traditional, centralized power infrastructure in China at the current juncture, it will undoubtedly rise to become the main source of electricity for not only rural communities, pastoral and mountainous areas but also urban and commercial areas on the merit of its unique advantages as the country works toward embracing renewables as the main source of future energy.

It is worth noting that while distributed renewable sources have a positive impact on the stability and safety of power systems, they can also pose certain challenges and risks. For one thing, distributed renewable power systems are independent of each other, and as such, large-scale power outages can be avoided and the problem of instability facing large-scale power grids is a non-issue. For another, the grid connection of distributed renewable systems also increases the variability and uncertainty of the load, in addition to causing voltage fluctuations in the grid and impacting the distribution relay protection of the system.

4.2.4 Analysis of the Impact of Policy on the Power Generation Mix

The development and evolution of China's power generation mix have been accompanied by the introduction and implementation of a series of policies. The transition of the energy system down the road, especially the development of renewable energy, will call for the continuing support of enabling policies. The adoption of the Renewable Energy Law in 2005 can be deemed as the beginning of China's outpouring of supportive policies for the development of renewable energies, especially wind and solar.

A close look at the evolution of China's power generation mix in the past two decades and the introduction of policies reveals the central role of policies in driving and supporting the country's energy transition. The Wind Farm Concession Program rolled out in 2003, the Renewable Energy Law promulgated in 2005 and the slew of policy documents for supporting wind power issued in the years that followed have fueled explosive growth in the installed capacity of wind energy since 2005. Coinciding with the rapid growth of China's PV capacity since 2009 was the aggressive introduction of a plethora of PV-related policies. In addition, following the release of policy documents on the absorption of wind power, China saw substantial reductions in curtailment in 2018 and 2019.

Renewable energy-related policies in China can be summarized as below:

(1) **Such means of financial support as loan discounts, subsidies and tax incentives are used to support the development of renewable energy**. In 1999, the Chinese government issued an official notice to further support renewable energy, which included the arrangement that renewable energy projects would be granted a 2% fiscal discount on lending rates by banks. A special fund for renewable energy was set up in 2006. Funds would be provided as grants or low interest loans, the repayment of which are accorded interest discounts up to a maximum of 3%. In terms of subsidies, in 2009, the Finance Ministry announced it would provide 20 yuan per watt peak (Wp) of subsidy for solar projects attached to buildings that have capacity of more than 50 kW peak. The conditions and amount of subsidies have been adjusted on an annual basis since. In 2012, China reduced the subsidy for projects under the Golden Sun program, geared towards end-users who generate the power for their own use, to 7 yuan per Wp. Solar PV subsidies have been declining as the sector grew. According to the *Notice on Matters relating to PV Power Generation in 2018*, jointly issued by the National Development and Reform Commission, the Ministry of Finance and the National Energy Administration, the subsidy for self-consumption DG generation projects was to be reduced by ¥0.05–¥0.32 kWh (including tax). DG projects that supply all generated power to the grid would be treated in the same manner price-wise as PV plants in the same resource area. Electricity generated for self-use from DG projects would be exempt from various fees including a reserve capacity charge and other grid-related service fees. Tax incentives are delivered primarily through Value-added Tax (VAT) policies. In 2013, China introduced a 50% VAT rebate for solar equipment manufacturers, effective between October 1, 2013 and December 31, 2015. The policy was renewed again in 2016.

(2) **The grid-price of electricity generated from renewable sources will use the benchmark grid-price of electricity as the starting point and transition toward more competitive prices in the long run, with the ultimate aim of delivering affordable or low-cost clean electricity**. The benchmark on-grid electricity price is set by the government while a competitive price is determined by competitive bidding under the upper limit of the government's suggested price. An affordable price generally refers to the benchmark grid-price of electricity produced locally from coal-fired units (including desulphurisation, denitrification and dust removal systems), and prices below this threshold are characterized as low-cost. A review of policies on the grid-price of renewable energy in the past two decades reveals a familiar pattern. Whether in the case of PV or wind power generation, including both onshore and offshore, the government would set a benchmark grid-price at the initial stage of development, gradually lower the price as the sector grew in both scale and the amount

of electricity generated, and then either replace the benchmark price with a government-suggested price or allow prices to be determined by competitive bidding in order to ultimately deliver clean electricity at affordable prices.

(3) **Policies to support wind energy in China began with the onshore sector and gradually expanded to include offshore wind farms**. The development of wind energy early on had been limited to onshore sites until the roll-out of the *Medium and Long Term Development Plan for Renewable Energy* in 2007, which proposed to "intensify research efforts toward the development of offshore wind energy technology, make preparations for the survey of offshore wind resources and pilot demonstration projects, and build 1–2 100,000-kW offshore pilot wind farms in order to acquire technology and experience for the large-scale development of offshore wind power in the future." In 2009, the *Interim Measures on the Management of Offshore Wind Farm Development*, the first policy document focusing exclusively on offshore wind power was released. Subsequently, policy documents on wind power would invariably include a separate section dedicated to the offshore sector. In terms of price, the grid-price of electricity generated from offshore wind farms has always been higher than that from onshore wind power plants. According to *the Notice from the National Development and Reform Commission on Improving the Policies for On-Grid Wind Power Prices*, the guideline feed-in tariff for onshore wind power varies among the four categories of wind energy areas as determined by the NDRC, specifically being 0.34, 0.39, 0.43 and 0.52 yuan/kWh in 2019, and 0.29, 0.34, 0.38 and 0.47 yuan/kWh in 2020. The guideline feed-in tariff for all offshore wind power projects stood at 0.8 yuan/kWh for the year 2019 and it was lowered to 0.75 yuan/kWh for 2020. It can be seen that while affordable access to electricity generated in category I and II wind energy areas is ensured, currently the grid-price of electricity generated from offshore wind farms remains much higher than that from thermal power plants in the same area.

(4) **Policy support was first provided to centralized PV power plants and gradually expanded to distributed PV projects**. *The Notice on the Implementation of the Golden Sun Demonstration Project* issued in 2009 specified that financial subsidies would be allocated toward supporting large-scale grid-connected PV power generation projects constructed in areas rich in solar energy potential. In 2013, the *Several Opinions of the State Council on Promoting the Healthy Development of the Photovoltaic Industry* proposed to commit significant resources toward developing the distributed PV power generation market and proceed with the construction of PV power stations in an orderly fashion. The National Energy Administration followed up again with yet another document on driving the implementation of support policies for distributed PV power generation a year later.

(5) **Policy on the development of renewable energy has evolved from a singular focus on the expansion of scale toward addressing such issues as integration and curtailment**. In 2012, the National Energy Administration issued the *Notice Regarding Improving the Connection and Consumption of Wind Resources.* Similar documents have been released each year since. The *Notice on Wind*

Power Investment Monitoring and Early Warning Results issued by the NEA in 2017 designated regions dealing with significant wind curtailment such as Inner Mongolia, Heilongjiang, Jilin, Ningxia, Gansu, and Xinjiang (including the Corps) as red warning zones, which would not be granted approval of the construction of any new wind power projects without first addressing wind curtailment. Since 2018, special notices issued for wind and PV power generation projects have spelled out strict prerequisites concerning the capacity of new projects to guarantee the efficient utilization of the electricity generated.

4.2.5 Projections on the Transition of China's Power Generation Mix

According to a 2017 study by the Institute for Contemporary China Studies of Tsinghua University, China's per capita GDP is expected to top US$36,632 by 2035 and US$60,847 by 2050 (Hu 2017). The country's annual electricity consumption per capita will reach the current Japanese level of roughly 8000 kWh in 2035. Since the industrial sector accounts for a larger share of the Chinese economy and consumes more electricity, it is estimated that annual electricity use per capita will top 8000 kWh by 2035 and 13,000 kWh by 2050, which is close to the current US level. According to the *National Population Development Plan (2016–2030)* released by the State Council, China's population is expected to peak at 1.45 billion in 2030, and then drop to 1.365 billion by 2050. Based on these projections, the country's overall power demand will reach 11.6 trillion kWh by 2030 and 17.8 trillion kWh by 2050.

Data on the hours of utilization of various power generating equipment for 2019 are shown in Table 4.6.

Literature (Mid-Term Evaluation and Optimization of the 13th Five-Year Plan for Electric Power 2019) proposed to expand China's hydropower installed capacity to 480 million kW by 2035; peak coal-fired installed capacity at around 1.3 billion kW by 2030; expand gas-fired installed capacity to 95 million kWh by 2020; and approve the construction of 8–10 nuclear power units annually.

Projections on the installed capacity and amount of electricity generated from various sources of energy are given on the basis of data presented above. It is presumed that from 2030 to 2050, the hours of usage of hydro, solar, wind, nuclear and thermal power facilities are 3800, 1500, 2200, 7000 and 4000 h, respectively.

Table 4.6 Utilization hours of various power generating equipment

Source	Hours of usage	Increase from the previous year
Hydro	3726	119
Solar	1284	55
Wind	2082	−21
Nuclear	7394	−149
Thermal	4293	−85

In 2005, 2014, and 2019, China's hydropower installed capacity stood at 110 million kW, 300 million kW and 360 million kW, respectively. Given the target of 480 million kW by 2035, it is predicted that hydropower installed capacity and the amount of power generated will total 450 million kW and 1.71 trillion kWh respectively by 2030. By 2050, China will have mostly tapped its full hydropower potential, with an installed capacity exceeding 90% of the technically exploitable hydropower capacity. Total hydropower installed capacity will reach 500 million kW and annual power generation will stand at 1.9 trillion kWh.

In 2019, the installed capacity of nuclear power in China was registered at 48.74 million kW, and the total capacity of reactors under construction topped 13 million kW. Assuming that 10 nuclear power units, each with a generation capacity of 1 million kW, are approved for construction each year, and each requires a construction time of 6 years, which has been the domestic average in recent years, China's nuclear installed capacity is expected to reach 100 million kW by 2030 and 300 million kW by 2050, producing some 700 billion and 2.1 trillion kWh of electricity respectively.

In order to meet the target of peaking carbon emissions by around 2030, new installations of coal power should be reduced year by year, and total coal-fired installed capacity should peak by 2030 at approximately 1.3 billion kW. Though natural gas is a cleaner form of energy than coal, its burning still yields a significant amount of carbon dioxide emissions. It is assumed that natural gas installed capacity will also peak by 2030. China's natural gas installed capacity stood at 76, 84 and 95 million kW respectively in 2017, 2018 and 2019. New installations amounted to roughly 10 million kW of added capacity annually. According to the latest data from the National Development and Reform Commission and the National Bureau of Statistics, natural gas output in China rose by 9.8% y-o-y to 173.62 billion cubic meters (bcm) in 2019. Its consumption was up by 9.4% to 306.7 bcm, with 44% of the country's gas demand satisfied by imports. China's natural resource profile dictates that its natural gas installed capacity won't be able to sustain continuous, high growth in the future, which is projected to reach 200 million kW by 2030. It is estimated, on the basis of coal and natural gas projections, that thermal installed capacity will peak at 1.5 billion kW by 2030, generating some 6 trillion kWh of electricity.

Assuming that the ratios of wind and solar installed capacity are the same in 2030 and 2050, and the annual time of usage of renewable facilities, calculated by averaging the hours of utilization of wind and solar facilities, is 1850 h, projections of China's power supply in 2030 and 2050 are shown in Tables 4.7, 4.8 and Fig. 4.18.

Table 4.7 Projections on China's installed capacity by source in 2030 and 2050. Unit of measurement: 100 million kW

Year	Thermal	Hydro	Nuclear	Renewables	Total
2019	11.9	3.6	0.5	4.1	20.1
2030	15	4.5	1	17.3	37.8
2050	14	5	3	44.3	66.3

It is projected that total installed capacity will grow to 3.78 billion kW by 2030. Thermal, hydro, nuclear and renewables including wind and solar will account for 40%, 12%, 2% and 46% respectively of the total. By 2050, total installed capacity is expected to climb to 6.63 billion kW, of which thermal, hydro, nuclear and renewables (incl. wind and solar) will represent 21%, 8%, 4% and 67% respectively.

4.3 Research on the Structural Transition of China’s Power Grids

The development of China’s power grids can be roughly divided into three stages:

The first stage: the formation of local/provincial power grids, spanning from the founding of the People’s Republic of China in 1949 to the late 1960s and early 1970s. In this stage, distribution networks centering around large and medium-sized cities were gradually connected through 220 kV transmission lines. And local power grids, mainly covering provincial areas and with 220 kV lines as the backbone network, were set up.

The second stage: inter-provincial connection, spanning from the early 1970s to the 1980s, when the improvement of provincial power grids and the formation of inter-provincial power grids went hand in hand. By the end of the 1970s, nearly 30 provincial power grids with 220 kV lines as the backbone gradually emerged in China,

Table 4.8 Projections on China’s power generation by source in 2030 and 2050. Unit of measurement: trillion kWh

Year	Thermal	Hydro	Nuclear	Renewables	Total
2019	5.1	1.3	0.3	0.6	7.3
2030	6.0	1.71	0.7	3.19	11.6
2050	5.6	1.9	2.1	8.2	17.8

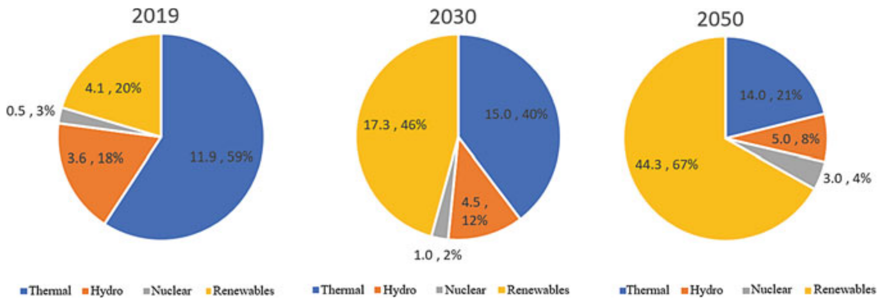


Fig. 4.18 Projections on China’s power generation mix in 2030 and 2050

which were interconnected into several regional grids across provinces. Since first launched in the early 1980s, the 500 kV transmission lines have become the backbone of major grids and served as the "liaison" across provinces and regions. By 1989, seven inter-provincial grids had taken shape in China, namely: the Northeast China Grid (NECG), North China Grid (NCG), East China Grid (ECG), Central China Grid (CCG), Northwest China Grid (NWCG), Sichuan and Chongqing Grid (CYG), and South China Grid (SCG) (including the Hong Kong Grid and the Macao Grid). Six other independent provincial grids existed in Shandong, Fujian, Hainan, Xinjiang, Tibet and Taiwan.

The third stage: the interconnection of cross-regional power grids, which began in the late 1980s and is now under rapid development. Milestones include:

- In September 1989, the ±500 kV UHV DC transmission project (1.2 million kW) between CCG and ECG was put into operation, marking the debute of asynchronous trans-regional interconnection in China and a major step forward from inter-provincial to cross-regional connection.
- In July 1991, China Southern Power Associated Company (the predecessor of China Southern Power Grid) was founded, mainly operating in Guangdong, Guangxi, Guizhou and Yunnan provinces (regions).
- In 2002, the State Council approved the reform plan of the power system to restructure grid and power production enterprises, which led to the establishment of State Grid Corporation of China (State Grid) and China Southern Power Grid (Southern Grid), with the former setting up five regional grid companies, namely, North China Grid Company Limited (NCGC), Northeast China Grid Company Limited (NECGC), Northwest China Grid Company Limited (NWCGC), East China Grid Company Limited (ECGC) and Central China Grid Company Limited (CCGC).
- Since the twenty-first century, the construction of the Three Gorges Project has facilitated the asynchronous interconnection between CCG and ECG, CCG and SCG, CCG and NWCG, as well as NECG and NCG. In December 2008, the UHV AC test and demonstration project between CCG and NCG was launched. In 2010, Xinjiang provincial grid and the main network of NWCG were connected through 750 kV lines. The year of 2011 witnessed the asynchronous networking between Tibet provincial grid and NWCG. By then, six regional grids had emerged: NCG, CCG, ECG, NECG, NWCG, and SCG.

Currently, the six regional grids are primarily connected through UHV AC/DC hybrid transmission lines—a reality determined by the severe regional mismatch between power and load distribution. UHV transmission lines enable long-distance, large-capacity and high-efficiency transmission of electricity, optimizing the allocation of energy resources nationwide.

4.3.1 UHV AC/DC Transmission Networks

4.3.1.1 Overview of UHV Transmission

The distribution of primary energy resources in China is quite the reverse to that of the main load. Some 80% of primary energy resources such as coal, water and wind are distributed in such remote areas as the western and northern regions with low population density, small energy demand, underdeveloped economy and large environmental capacity, while over 75% of energy consumption is concentrated in economically developed and densely populated eastern regions such as Beijing-Tianjin-Tangshan area, Yangtze River Delta and Pearl River Delta. With the growth of national economy, industrialization and the improvement of people's living standards, China will continue to see surging power demand. With this in mind, large-capacity and long-distance transmission projects hold the key to energy balance. And the scenario of massive west-to-east power transmission will remain well into the future (Zhou et al. 2018).

HVAC and HVDC transmission projects developed rapidly in China. On January 6, 2009, the 1000 kV Southeast Shanxi-Nanyang-Jingmen UHV AC pilot demonstration project, the first of its kind in China, was put into operation. It marked the world's first 1000 kV transmission line for commercial use, harnessing complementary hydro and thermal power production from NCG and CCG. On December 28, 2009, Southern Grid's ±800 kV UHV DC transmission project extending from Yunnan to Guangdong, independently designed by China, went into operation, meaning that China had joined the ranks of world-leading nations in the research on key technologies of UHV DC transmission and transformation and manufacturing of crucial equipment. China had built nine UHV AC and ten DC lines by June 2019 and is building another three UHV AC and one DC lines. The total length of operating UHV lines in the country amounted to 27,570 km, and the total transformation (conversion) capacity stood at 296.2 million kVA (kW). By the end of 2019, China's UHV lines had delivered more than 1.15 trillion kWh of electricity cumulatively, making tremendous contribution to stable power supply, clean energy development, environmental improvement and grid safety. UHV AC and UHV DC power transmission projects won the National Science and Technology Progress Awards in 2012 and 2017 respectively.

At present, AC/DC transmission projects among regional power grids in China mainly include:

- SCG-CCG: ±500 kV Three Gorges-Guangdong DC transmission project (2003);
- NECG-NCG: ±500 kV Gaoling Back-to-Back DC transmission project (2008, 2012), ±800 kV Zhalute-Qingzhou DC transmission project (2017), 1000 kV Southeast Shanxi-Nanyang-Jingmen UHV AC transmission project (2008);
- NWCG-CCG: Lingbao Back-to-Back DC transmission project (2009), ±500 kV Debao DC transmission project (2009), ±800 kV Tianzhong DC transmission project (2014), ±800 kV Jiuquan-Hunan DC transmission project (2017);
- NCG-NECG: ±660 kV Yindong DC transmission project (2010), 1000 kV Yuheng-Weifang UHV AC transmission project (2017);

- CCG-ECG: ±500 kV Ge Nan DC transmission project (1989), Long Zheng DC transmission project (2003), Yi Hua DC transmission project (2006), Lin Feng DC transmission project (2011), ±800 kV Upward DC transmission project (2010), Jinping-South Jiangsu DC transmission project (2012), Left Bank of Xiluodu-Jinhua, Zhejiang DC transmission project (2014);
- NWCG-ECG: ±800 kV Ningdong-Zhejiang DC transmission project (2016);
- NECG-ECG: ±800 kV Ximeng-Taizhou DC transmission project (2017);
- NCG-ECG: ±800 kV North Shanxi-Jiangsu UHV DC transmission project (2017).

The UHV AC transmission projects set to be completed in 2020 include "west vertical" and "mid vertical" lines, the former being the UHV AC line from west Mongolia to south Hunan, and the latter being the UHV AC line from Ximeng to Zhangbei to Ganzhou, with a total capacity of 17 million kW, serving central and north China respectively. UHV DC transmission projects include Huaidong-South Anhui, Qinghai-Henan, Yazhong-Jiangxi and North Shaanxi-Wuhan lines. The voltage of Huaidong-South Anhui line is ±1100 kV with a capacity of 12 million kW, while the other lines are ±800 kV and 10 million kW, also serving central and north China.

4.3.1.2 UHV DC Transmission Network

High voltage direct current transmission (HVDC) technology is very important in long-distance and large-capacity power transmission, asynchronous networking of power systems, improvement of reliability, and new energy development and its grid connection. It is one of the major grid technologies and produces tremendous impact on grid structure.

A late mover in DC transmission technology, China independently built the first DC transmission line running from Zhoushan to Ningbo in 1987. Thanks to three decades of development, enormous strides have been made in conventional HVDC transmission, with notable improvement in voltage classes, transmission capacity and distance, localization of equipment and engineering, etc. For China's HVDC projects, their voltage classes range from ±400 kV (Golmud-Lhasa HVDC project) to ±1100 kV (Changji-Guquan UHV DC project); the capacity varies from 600 MW (Golmud-Lhasa HVDC project) to 12,000 MW (Changji-Guquan UHVDC Project); transmission length is between 890 km (Three Gorges-Changzhou HVDC project) and 3324 km (Changji-Guquan UHVDC project). On the whole, China's UHV DC transmission is featured by high and multiple voltage classes, wide span in capacity and transmission length.

Equipment for HVDC transmission mainly includes converters, converter transformers, smoothing reactors, AC filters, DC arresters and control and protection equipment, as shown in Fig. 4.19 (Wang and Cao 2018). Converters are used for rectification and inversion, during which higher harmonics will be produced. In this case, filters should be configured on the AC bus of converter station to reduce the entry of higher harmonic into the AC system. The filter consists of reactance coil, capacitor and small resistor connected in series.

According to the Annual Development Report on China Power Industry 2019 released by CEC in June 2019, by the end of 2018, China's cross-regional power transmission capacity totalled 136.15 million kW, 122.81 million kW of which were connected to AC and DC networks. The power transmission capacity of cross-regional point-to-network stood at 13.34 million kW.

The Annual Report on National Power Reliability 2017 issued by CEC in May 2018 revealed statistics of varied HVDC transmission systems (15 point-to-point EHV systems, 7 point-to-point UHV systems and 3 back-to-back systems), as shown in Table 4.9. All systems featured over 90% of energy availability, which demonstrates the maturity and reliability of UHV DC transmission technology in China's engineering practice.

In the foreseeable future, China's conventional HVDC transmission technology will largely remain unchanged, but will reach higher voltage class, larger transmission capacity, longer transmission and lower cost per unit of construction in the long run (Jia 2018).

4.3.1.3 UHV AC Transmission Network

In recent years, China has seen a string of major technological breakthroughs in key UHV technologies, thanks to intensive R&D efforts in automatic voltage control, secondary-arc current control, commissioning and operation of equipment sets. As a result, China has owned a whole set of world-leading UHV AC transmission technologies with independent intellectual property rights (IPRs). On January 6, 2009, the Southeast Shanxi-Nanyang-Jingmen UHV AC pilot—a 1000 kV AC power transmission and transformation project that was developed, designed and built by China

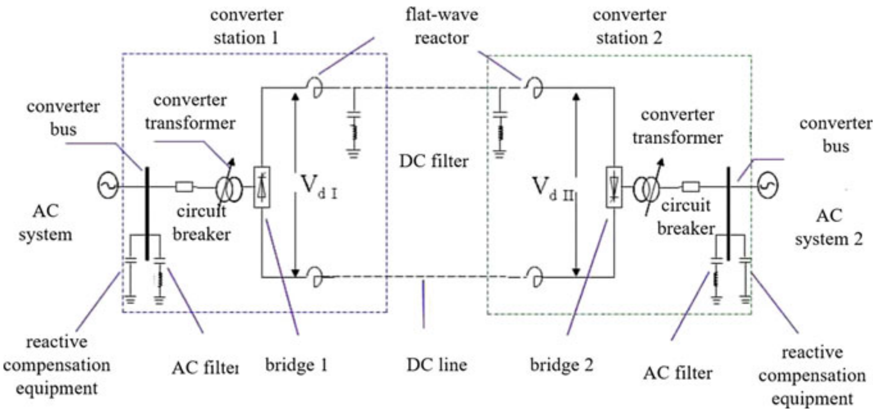


Fig. 4.19 Schematic diagram of HVDC transmission

Table 4.9 Reliability comparison of nationwide HVDC transmission systems in 2016 and 2017

Reliability indicators	Year	Types of HVDC transmission systems			Total
		Point-to-point EHV	Point-to-point UHV	Back-to-back	
Number of systems	2016	14	6	3	23
	2017	15	7	3	35
Rated transmission capacity (MW)	2016	37,964	39,600	4860	
	2017	41,164	47,600	4860	93,624
Energy availability rate (%)	2016	96.003	93.112	96.971	94.671
	2017	95.808	94.885	96.030	95.350
Number of forced outages	2016	20	14.5	6	40.5
	2017	19	11	3	33
Unavailability rate of forced energy (%)	2016	0.061	0.167	0.749	0.152
	2017	0.172	0.208	0.015	0.182
Unavailability rate of planned energy (%)	2016	3.936	6.723	2.287	5.178
	2017	4.022	4.908	3.955	4.469
Total electricity transmitted (100 mln kWh)	2016	1711.56	1913.23	297.48	3922.27
	2017	1891.86	2240.89	330.16	4462.90
Energy utilization (%)	2016	51.32	55.00	69.68	54.17
	2017	52.46	53.74	77.55	54.42

Note In Table 4.9, reliability evaluation indicators such as energy availability rate, unavailability rate pf forced energy, unavailability rate of planned energy, and energy utilization are calculated by weighting each system based on rated transmission capacity

with IPRs—was put into trial operation. This is the first of its kind in China, showcasing major breakthroughs in the localization of long-distance, large-capacity and low-loss UHV core technologies and equipment, which was crucial for optimizing resource and energy allocation, and ensuring national energy security and reliable power supply (Tang et al. 2016).

As of 2019, China's UHV AC transmission projects already in operation and under construction include:

- 1000 kV Southeast Shanxi-Nanyang-Jingmen UHV AC pilot demonstration project (2009), with a conversion capacity of 18 million kW;
- 1000 kV Huainan-North Zhejiang-Shanghai UHV AC demonstration project (2013), with a conversion capacity of 21 million kW;
- 1000 kV North Zhejiang-Fuzhou UHV AC project (2014), with a conversion capacity of 18 million kW;

- 1000 kV Ximeng-Shandong UHV AC project (2016), with a conversion capacity of 15 million kW;
- 1000 kV West Mongolia-South Tianjin UHV AC project (2016), with a conversion capacity of 24 million kW;
- 1000 kV Huainan-Nanjing-Shanghai UHV AC project (2016), with a conversion capacity of 12 million kW;
- 1000 kV Ximeng-Shengli UHV AC project (2017), with a conversion capacity of 12 million kW;
- 1000 kV Yu Heng-Weifang UHV AC transmission and transformation project (2017), with a conversion capacity of 15 million kW.

4.3.1.4 Comparison of Two Technological Options

China's UHV transmission network has always been characterized by a combination of AC and DC. The replacement of UHV AC grid by UHV AC backbone network and proper utilization of UHV AC/DC transmission for regional grids interconnection and synergy have proved to be vital to power delivery from major energy production bases and power transmission to remote areas (Peng et al. 2017).

Meanwhile, both technology options have their own characteristics. UHV DC transmission technology is featured by Zhou and Zhong (2007): (1) large transmission capacity, high voltage class, narrow line corridor, suitable for high-power transmission in long distance; (2) no drop point, clear and simple architecture, and direct transmission of power to the load center without synchronous operation between networks; (3) equipment compromise by high-power impact on the AC system at both ends due to DC system locking.

UHV AC transmission technology is featured by Zhou and Zhong (2007): (1) large transmission capacity, wide coverage, minor network loss, small number of transmission corridors, and suitable for large-capacity transmission in short distance; (2) existence of drop point, the ability of building backbone network based on actual needs of power distribution, load position, power transmission and exchange; (3) variation of transmission power affects reactive power at the transmitting and receiving ends, triggering chain reaction and even voltage instability.

In contrast to UHV AC, UHV DC long-distance transmission boasts low construction cost of long-distance overhead lines (as shown in Fig. 4.20) (Wen et al. 2012), minor loss, large transmission capacity, narrow transmission corridors, easy access to long-distance transmission, high reliability and high energy utilization (as shown in Tables 4.10 and 4.11), etc.

With the rapid development of UHV transmission network in China, notable changes have occurred in the running of power grids, with some regions experiencing much stronger DC than AC (Zhang and Gong 2016). Overlapping UHV AC synchronous grids on the existing trans-regional UHV DC transmission would produce a complex parallel of AC and DC, which is prone to new stability issues and might incur potential security risks. Therefore, grid security and reliability should warrant more attention.

It’s important for UHV AC/DC parallel grids to match the distribution of energy resources in China. Construction of robust UHV grids should be accelerated by using UHV DC, via UHV AC connection, to transmit clean energy across regions and over long distances. Efforts should be made to reverse the precedence of DC over AC and ensure appropriate balance, so that the size of DC or AC is commensurate with intensity. Currently, China’s UHV AC/DC parallel grids have taken shape, yet new problems resulting from constant changes in operation stand as a test to the endurance of grids (Wen et al. 2012).

4.3.2 Flexible DC Transmission Technology

Despite the distinct strength of UHV DC transmission technology in long-distance transmission, it can only be applied to point-to-point transmission of energy without any drop point in the middle, which is not conducive to the optimal allocation of

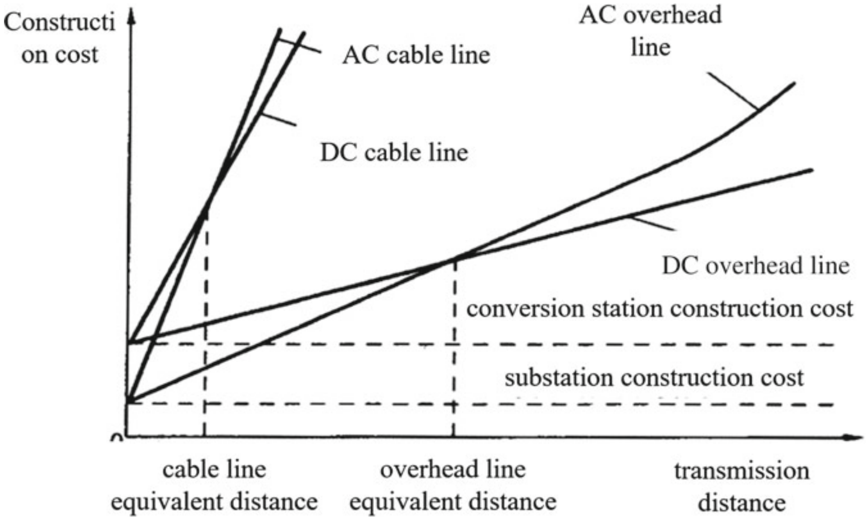


Fig. 4.20 Comparison of AC/DC transmission construction costs

Table 4.10 Reliability comparison of AC and DC networks

Name	AC		DC	
	Single-circuit	Double-circuit	Monopolar	Bipolar
Line (times/100 km/year)	0.299	0.054	0.126	0.055
Two-end conversion stations (times/year)	0.56	0.12	4.8	0.2

Table 4.11 Comparison of energy unavailability rates of AC/DC networks

Name	Electricity unavailability rate (%)			
	50% loss in of transmission capacity		100% loss in transmission capacity	
	AC	DC	AC	DC
Line	0.75	0.07	0.05	0.016
Transformer (conversion) station	0.07	0.62	0.007	0.002
Total	0.82	0.69	0.057	0.018

electricity in many cases. Flexible DC transmission technology helps overcome this weakness and represents the future of grid development.

In 1990, Canadian scientists envisioned flexible DC transmission technology by adopting insulated gate bipolar transistor (IGBT) and integrated gate converter thyristor (IGCT) and other fully controlled devices, which captured attention from scholars and researchers worldwide. Leading international electric academic organizations named it "VSC-HVDC" ("high-voltage direct current transmission with voltage source converter"), or "flexible DC transmission" in China.

Flexible DC transmission technology is able to control the flow of electric energy and isolate faults by using turnoff voltage source converters and pulse width modulation (PWM); it can absorb energy, adjust active and reactive power in the operation of power grids to improve voltage stability; in case of flow reverse, voltage polarity can be kept unchanged for multi-end transmission; AC side current can be controlled to cut short-circuit current and reactive compensation capacity; filtering devices can also be reduced. The earliest flexible DC project was Hellsjon, which was put into operation in Sweden in 1997. The first interconnected flexible DC transmission project was Directlink in Australia, and the first back-to-back flexible DC project was EaglePass-TexasB2B between Mexico and US.

In 2011, Shanghai Nanhui flexible DC project, the first of its kind in China based on MMC technology, was officially launched. The project was designed and manufactured by the State Grid, which signified China's capability of independent R&D, design and manufacturing of key equipment and control technology for flexible DC transmission. Since then, China has been at the forefront of MMC-HVDC technology development. In 2013, 200 MW/±160 kV Nan'ao three-terminal flexible DC transmission demonstration, the world's first multi-terminal MMC-HVDC project, was commissioned. Designed and manufactured by China Southern Power Grid, it managed to address key technical problems such as large-scale wind farms access through MMC-HVDC, multi-terminal system control and protection, and complex AC/DC hybrid system control, laying a solid foundation for the application and promotion of flexible DC transmission access technology for large wind farms in China, and marking a significant stride for China's transmission technology towards multi-terminal flexible DC system.

In China, flexible DC transmission projects have been constructed in Nanhui (±30 kV, 18 MW, 2011), Nan'ao (±160 kV, 200 MW, 2013), 5 terminals of Zhoushan (±200 kV, 400 MW, 2014) and Xiamen (±320 kV, 1000 MW, 2015), which have been running in a stable manner and gained valuable experience in construction and operation. The Zhangbei DC power grid (±500 kV, 3000 MW) that has been fully connected also represents the multi-terminal flexible DC transmission network with the highest voltage class and the largest capacity in the world. The design of the hybrid DC network under construction in Wudongde (±800 kV, 5000 MW) has also been upgraded. Both projects are expected to be commissioned in 2020.

Compared with traditional HVDC transmission, flexible DC boasts the following advantages:

(1) Reactive power is not required on the AC side with no commutation failure. For traditional HVDC transmission, conversion stations need to absorb tremendous reactive power, which calls for many more devices for compensation; what's more, traditional DC transmission relies on voltage support of AC system during commutation. Inadequate support might result in commutation failure—a problem that would never occur in flexible DC.
(2) Flexible DC transmission technology can operate in 4 quadrants and control active and reactive power independently, providing power supply to passive networks. Flexible DC transmission can be used as STATCOM application to compensate reactive power on AC side and stabilize its voltage. But traditional DC transmission can operate in 2 quadrants only without independent control of active and reactive power.
(3) Minor harmonic content requires almost no filters due to the fairly high switching frequency of flexible DC transmission.

In view of these advantages, flexible DC transmission technology is mainly applied in the following scenarios:

(1) Massive power transmission and networking of AC/DC systems.
(2) Grid connection of distributed power.
(3) Grid capacity expansion and DC power supply. The less harmonic content during the operation of flexible DC transmission system enables quick control of system-wide power to upgrade power quality; less floor space is required for flexible DC transmission conversion stations than traditional ones, hence more land saving and less waste; furthermore, the ability of the system to control the current on AC side as needed makes control of short-circuit capacity possible.
(4) Power supply to weak systems or isolated islands. No voltage is needed from the outside for flexible DC transmission systems during commutation, and the system could be run in passive inversion and the passive network can be used as a receiving system to ensure stable power supply to remote areas. But reliability remains a challenge for overhead flexible DC transmission lines.

The development of high-voltage and large-capacity flexible DC transmission projects entails urgent measures to enhance the capacity, voltage level and reliability of power electronic devices. More efforts are needed to slash the cost and facilitate large-scale construction of new DC grids and the maintenance and renovation of existing ones. To accommodate large capacity, a gradual migration is required from IGBT module packaging and compression IGBT to compression IGCT in order to provide high reliability. From the material standpoint, it's important to introduce gallium arsenide and silicon carbide as new wide band gap semiconductor materials to enable larger capacity of single semiconductor switch components. The concurrent localization efforts have brought about tremendous cost reduction. And the development of high-voltage and large-capacity equipment will greatly contribute to new breakthrough in the performance of power electronic equipment. It is projected that by 2050, key research findings from new semiconductor materials will be commercialized for massive production, with 100% localization and a big boost in the capacity and performance of equipment.

Major breakthroughs have been made in power electronics related equipment of flexible DC grids, with substantial improvement in performance of such equipment as modular multilevel converters, DC circuit breakers and DC transformers, which have seen increasing local production. To illustrate, the performance of DC circuit breakers in Zhoushan's 5-terminal flexible DC network launched in 2016 has achieved 200 kV/15 kA/2.64 ms. Not only that, the performance of breakers in Zhangbei 5-terminal flexible DC network set to operate in 2020 has hit a new high of 500 kV/26 kA/2.64 ms, and its multi-level power electronic converter has also broken a new world record of 500 kV/3000 MW. With further upgrade in the capacity of converters, circuit breakers and other equipment, construction of flexible DC networks with larger capacity and in a wider range could be made possible by 2050.

Core power electronic devices in DC transmission (such as high-voltage high-capacity IGBT, IGCT, IETO, etc.) are expected to be fully localized in the future, and new semiconductor devices with large capacity, low cost and high reliability will be developed. Flexible DC core equipment such as modular multilevel converter (MMC), DC circuit breaker and DC transformer will be fully commercialized. As an increasingly more economically attractive option than traditional high-voltage DC transmission, flexible DC transmission is likely to be adopted as the mainstream technology for long-distance high-capacity transmission and grid interconnection. Flexible transmission and distribution technologies will produce dramatic impact on grid structure, which will be distinctly featured by the hybrid of AC/DC and multi-directional transmission. The share of distributed power supply and energy storage will be significantly increased, and energy self-sufficiency of regional grids will be improved, with a notable downsizing of backup capacity.

4.3.3 DC Distribution Network

The rapid development and wide application of new energy, information technology and power electronics technology has prompted rising demand for the amount, quality and reliability of power, which has in turn created challenges to the existing AC distribution networks in terms of distributed new energy access, diversification of load and power demand, stability and economic efficiency of power supply, etc. As urban planning has been detached from power system planning in China, the distribution network structure is not fully aligned with load development, so the planning and development of distribution networks and power quality increasingly fall short of the demand of urban development (Liu et al. 2015).

DC power grids have been mainly built on the flexible DC transmission technology. Compared with conventional DC transmission, flexible transmission requires no commutation voltage from the AC grid, and thus is highly suitable for such scenarios as isolated power supply, access to renewable power, capacity expansion and renovation in cities. In the technical report of the CIGRE working group B4.52, DC power grid is defined as a direct current network composed of a radial network of converters. DC grid is characterized by higher redundancy and more flexible and diversified operation than traditional flexible DC transmission (Boroyevich et al. 2010).

Different from AC distribution grid, power load of DC distribution grid is supplied by DC bus, which requires no extra rectifier equipment for power supply when applied to settings with large DC load, demonstrating greater advantages of application. DC distribution network features minor line loss, high reliability and strong access to distributed power supply with no need for phase-frequency control (Sun et al. 2016). The basic topological structure of DC distribution network includes ring, radial and two-terminal distribution, etc. Power supply of radial network is less reliable, but is much easier for control and protection; while that of ring network enjoys high reliability, but lacks control and protection.

Existing DC power distribution systems, such as the SBN (Sustainable Building and NanoGrids) (Marquardt 2011) proposed by Virginia Tech University of United States, adopt two voltage classes of 380 and 48 V to form a radial topology. The FREEDM (Future Renewable Electric Energy Delivery and Management) system brought up by North Carolina State University is a plug-and-play radial network (Marquardt 2011). At present, DC power distribution networks have been applied in communication power distribution, vessel power distribution and subway electric traction, etc., but the application of ring network has been a rarity, and no standards have been formulated for the selection of voltage class for corresponding DC distribution network.

On the whole, technologies for the planning and application, scheduling and control, safe operation and protection of DC distribution network are not yet mature. But with the cost reduction of power electronic devices, development and application of DC circuit breakers, flexible access of distributed energy, and fault current limits of the network, DC distribution network will promise a brighter prospect for adoption (Yan et al. 2019).

4.4 Research on Coordinated Development of Generation Mix, Grid and Load of Power System in China

4.4.1 Research on the Trend of Load Variation

In-depth analysis and accurate prediction of load characteristics are important guarantees for reliable, efficient and economical operation of power systems. In recent years, major changes have occurred in the external environment affecting the load and load characteristics of power grid, which are mainly shown in the following areas: (1) the economy has entered a phase known as the "new normal", with accelerated structural adjustment that has exerted great impact on load composition; (2) market-based reform and liberalization of electricity sales would make for closer interaction between users and grid, hence changes in the load curve; (3) rapid growth in electric vehicles and other new electricity loads would bring considerable impact on load curve; (4) rapid development of distributed energy would be a useful supplement to the main grid, hence the importance of managing the impact of distributed energy development on grid load.

With the influence of multiple factors such as distributed energy, power market, demand response, electric vehicles and energy storage, generalized load is featured by:

(1) Diverse load components. Traditional loads mainly involve electric motors, electric furnaces, lighting equipment and other electrical equipment that consume power externally. The generalized load not only involves the electrical equipment in the traditional load, but also distributed power such as distributed wind and distributed PV, as well as active loads such as energy storage and electric vehicles that can participate in demand side response.

(2) Diverse impact factors. Traditional load is mainly affected by macroeconomic, demographic, meteorological and other factors, which also bring impact on the generalized load. In addition, the generalized load is also subject to many other factors. For instance, distributed wind and solar are affected by wind speed, wind direction, light radiation, cloud cover and other natural elements. The load of electric vehicles is under the impact of traffic conditions, user travel patterns, among others. Active load participation in demand management is subject to market price and demand response strategy. These factors often come together in impacting generalized load, which renders load characteristics more complex.

(3) Both "load" and "generation" characteristics. When the output of distributed power supply is less than the electricity demand at the access node, the node would present the characteristics of load. And in case of greater distributed energy output than power load at its access node, the remaining energy would be transmitted to the grid, and the reverse power flow occurs, showing features of power generation. With both "load" and "generation" characteristics, this type of generalized load adds great difficulty to the planning of distribution network and calculation of power flow.

(4) Ability to respond. Active loads such as energy storage and electric vehicles can change their energy consumption according to demand response. Active load can cater to the change in electricity prices and shift the load from the period with high tarrif to the one with low prices. In this way, load can be balanced through proper tarrif scheme. Active load can also boost the uptake of renewable energy via demand response and reduce the adverse impact of renewable energy access. The ability of generalized load to respond improves the safety and economy of power system operation, and may change the original curve shape and characteristics of load.

(5) Strong uncertainty. The uncertainty of generalized load comprises the uncertainty of user demand, the uncertainty of distributed renewable energy output, and the uncertainty of active load response. The combined influence of multiple uncertain factors leads to great uncertainty of generalized load, bringing new challenges to the planning and operation of power grid.

(6) Complex spatio-temporal characteristics. Due to the blend of diverse factors on different scales of time and space, generalized loads show complex temporal and spatial characteristics. To illustrate, generalized load at a certain point may correlate with meteorological factors, electricity prices, and renewable energy output at different previous time, meaning that it is correlated on multiple time scales. The generalized load possesses complex spatio-temporal characteristics, placing higher demands for its description, analysis and prediction methods.

Figure 4.21 illustrates the annual electricity consumption in China from 2000 to 2018. The dawn of this century witnessed rapid economic development, which pushed up demand for electricity, and the use of power rose rapidly. As time went by, China's economy has shifted from high-speed to high-quality growth, bringing a gradual slowdown of power demand, and subsequently steadier increase in electricity use. It is projected that electricity consumption will continue to grow steadily in 2020. Without widespread extreme weather, power consumption across the country will be up 4–5% in 2020, with an overall balance of supply and demand. At the regional level, northern and central China are expected to experience power shortage at certain time slots; eastern and southern China are expected to see an overall balance; and a surplus of power supply might be found in northeastern and northwestern regions.

In 2019, nationwide electricity consumption amounted to 7.23 trillion kWh, up 4.5% over the previous year. The country's per capita consumption was 5161 kWh, and the per capita residential use was 732 kWh. The growth of electricity consumption in Q1, Q2, Q3 and Q4 was 5.5%, 4.5%, 3.4% and 4.7%, respectively. The main characteristics of electricity consumption are:

First, electricity consumption in the primary industry showed steady increase. In 2019, the industry consumed 78 billion kWh of power, up 4.5% from the previous year. The industry contributed 1.1% to the growth of power consumption in the whole country.

Second, electricity consumption of the secondary industry maintained medium-low growth. In 2019, the industry used 4.94 trillion kWh of power, an increase of 3.1% over the previous year. Quarterly growth was 3.0%, 3.1%, 2.7% and 3.5%,

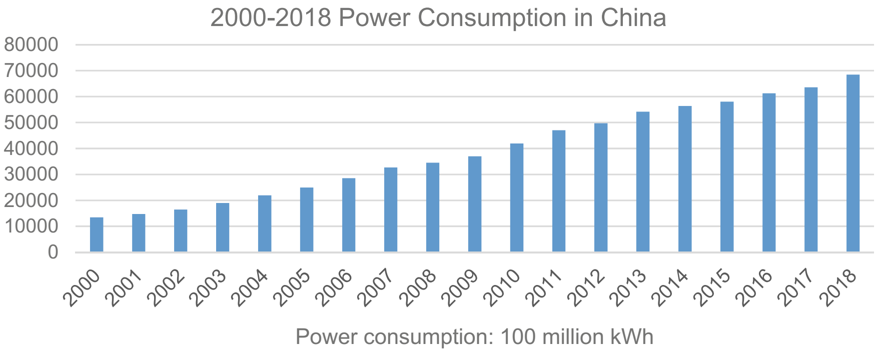


Fig. 4.21 Annual power consumption in China from 2000 to 2018

respectively. Consumption in the industry accounted for 68.3% of the national total, and contributed 47.9% to the growth of electricity use in the whole society.

Third, electricity consumption in the tertiary industry maintained rapid growth. In 2019, the industry used 1.19 trillion kWh, up 9.5% over the previous year, with quarterly growth of 10.1%, 8.6%, 7.7% and 11.8%, respectively. The tertiary industry and urban and rural residential use contributed 51% to the growth of electricity consumption.

Based on the clustering algorithm, the load patterns of various industries in China can be classified into the following categories: (1) "M" shape; (2) "∏" shape; (3) "__" shape; (4) "W" shape, as shown in Table 4.12. The "M" load curve has double peaks, which usually occur at 9–12 a.m. and 14–17 p.m., primarily in agriculture, forestry and animal husbandry in the primary industry, as well as labor-intensive sectors in the secondary industry and equipment manufacturing; "∏" curve mainly appears in the tertiary industry and sectors with uninterrupted noon production in the secondary industry; The "__" curve is very stable, which is mainly found in the part of secondary industry that requires continuous production and "three shifts"; The "W" mainly takes place in the secondary industry, with strong peak averting behaviors.

4.4.2 Research on Demand Response Mechanism

With the vision of high renewable energy uptake, load participation in system operation via demand response becomes a necessary technical behavior. The US Department of Energy defines demand response as a change in the electricity consumption pattern by end-users in response to real-time changes in electricity prices, or the changes in consumption pattern of users in response to economic incentives when prices are high or system reliability is threatened. China released *Measures on Power Demand Side Management (DSM)* in 2010, which signalled the official launch of

Table 4.12 Categories of typical daily load curve of sectors in China

Industry category	Sector name	Type of curve	Industry category	Sector name	Type of curve
Primary industry	Agriculture	M	Secondary industry	Oil and gas extraction	—
	Forestry			Forestry ferrous metal mining and dressing	
	Animal husbandry			Textile	
Secondary industry	Non-metallic mining and dressing			Paper and paper products	
	Textile and apparel			Petroleum/coal and other fuel processing	
	Leather/fur/feather and its products and footwear			Chemical raw materials and chemical products manufacturing	
	Wood processing and wood/bamboo/rattan/palm/grass industry			Ferrous metal smelting and rolling processing	
	Furniture manufacturing			Non-ferrous metal smelting and rolling processing	
	Printing and recording media reproduction			Computer/communication and other electronic equipment manufacturing	
	Culture and education/industrial art/sports and entertainment products manufacturing			Coal mining and washing	W
	Pharmaceutical manufacturing			Nonferrous metal mining and dressing	
	General equipment manufacturing			Agriculture and sideline food processing	
	Special equipment manufacturing			Chemical fiber manufacturing	
	Automotive manufacturing			Non-metallic mineral products	
	Railways, ships, aerospace and other transportation equipment manufacturing			Metal products	
	Electrical machinery and equipment manufacturing			Comprehensive utilization of waste resources	
	Instrumentation 4-manufacturing		Tertiary industry	Finance	∏
	Building			Real estate	

(continued)

Table 4.12 (continued)

Industry category	Sector name	Type of curve	Industry category	Sector name	Type of curve
	Rubber and plastic products	∏		Leasing and commercial service	
	Tobacco products			Public service and management organization	
Tertiary industry	Information transmission. software and information technology service			Wholesale and retail	
	Accommodation and catering			Transport/storage/postal	

demand response mechanism in China. In 2015, the CPC Central Committee and the State Council jointly issued *Several Opinions on Further Reform of the Power System*, kicking off a new round of market-based reform of the power system, building a solid foundation for the massive application of demand response. In recent years, Beijing, Shanghai and other cities have implemented a number of demand response pilot projects, which have proved to adjust the load quickly an flexibly, and reduce peak time power demand, thus verifying the engineering practicability of demand response.

Demand response technology enables power users to change their electricity consumption behavior according to the price signal or incentives of the market, in order to achieve "peak shaving" and make the power load flexible. Demand response drastically changes the mode of traditional power grid in which power supply goes with the load, taking the dispatchable resources on the demand-side as the alternative resources on the supply side. As a virtual controllable resource, demand response can be combined with a various types of power generation to overcome the adverse impact of randomness, volatility and load mismatch of new energy on the power grid, properly absorb renewable energy output, thereby providing flexibility to the system.

As an efficient load management mechanism, demand response can be grouped into two categories (Fig. 4.22): one based on prices and the other based on incentives. The former refers to the adjustment of power consumption, time and mode by users according to market price signals, which mainly includes time-of-use (TOU) tarrif, peak tarrif and real-time tarrif, etc. The latter refers to the incentives (compensation, discount, etc.) used by relevant organizations to motivate and encourage users' involvement in load reduction, taking the load of contracted users as virtual standby resource and scheduling it. The incentive demand response mainly includes interruptible load control, direct load control and demand-side bidding, etc.

In recent years, demand response technology has been widely used in many power markets, including PJM power market in the United States, NYISO power market and National Grid of the United Kingdom. At present, there is still a distance between China's power market and developed countries, and demand response technology has

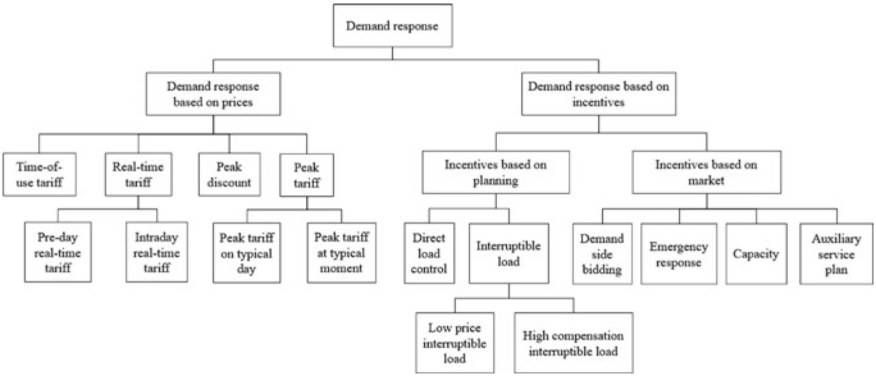


Fig. 4.22 Technical categorization of demand response

not maximized its benefits in the power market. Utilizing demand response resources and improving demand-side flexibility in the power system with high proportion of renewable energy will be the top priority in the future power system development.

Since 2002, the smart grid development strategy has stressed the need to ease power shortage and absorb clean energy by adopting demand response. Afterwards, a series of policies were unveiled to strengthen its development. In 2012, Ministry of finance, National Development and Reform Commission approved Beijing, Tangshan, Suzhou, Foshan to be the first national pilot cities for DSM. In 2018, the country achieved the maximum peak power reduction of 12.45 million kW through demand response. At present, it is believed that demand response is mainly used for relieving power shortage by balancing the load and making its curve flexible. But in the future it should be more about ensuring the smooth operation of high-proportion renewable energy systems. The National Grid Energy Research Institute estimates that with the accelerated electrification, demand response resources will reach 370 GW by 2050.

4.4.3 Research on the Coordinated Development of Flexible and Balanced Generation, Grid and Load

Power system flexibility refers to the ability of a power system to adapt to random changes in power generation, grid and load at a certain cost by optimizing the allocation of available resources in the active balance of a time-scale. Based on the above definition and actual operation of the power system, five characteristics of power system flexibility could be defined, as shown in Table 4.13.

A look at new energy development in China in recent years shows that the lack of flexible resources has become one of the key impediments for the consumption of renewable energy. Despite the boom of China's new energy in recent years, with the installed capacity of wind and solar exceeding 210 million kW and 200 million kW respectively in 2019, ranking the first in the world, serious curtailment of wind and solar have also occured. According to the data from the National Energy Administration, wind curtailment from 2012 to 2017 averaged at 12.6%; and that in most of the wind farms in the Three Northern regions even exceeded 20%. The reasons for load-shedding vary from region to region, but in essence, the uptake of renewable energy is hampered by the lack of flexibility in the power system. For power grid in north Hebei and Gansu, the main reason is the lack of power consumption and flexibility incentives; for western Inner Mongolia and three northeastern provinces, it's mainly due to the long heating period with insufficient peak regulation of conventional units. In 2018 and 2019, the government and the industry worked hard to address wind and solar curtailment, and the wind curtailment was brought down to 7 and 4%. Figure 4.23 shows the active power balance of the system in low and high uptake of renewable energy scenarios.

Currently, with the low percentage of renewable energy and lower level of volatility and uncertainty, flexibility could take a back-seat in the planning until the system is scheduled for operation. Wind and solar curtailment resulted from inflexibility in isolated areas and timeslot of the system is acceptable from an engineering standpoint. If inflexibility occurs in the future scenario with a high uptake of renewable energy in the power system, the problem will be even worse, with widespread wind and solar curtailment and a subsequent system failure, thus putting

Table 4.13 Characteristics of power system flexibility

Characteristics	Connotations	Examples
Directionality	Upward power adjustment Downward power adjustment	Load increase (reduction in renewable energy) Load decrease (increase in renewable energy)
Multi-spatial-temporal characteristics	Flexible supply and demand are related to the time scale and are subject to space constraints	Frequency modulation (≤15 min), ramping (15 min–4 h), peak regulation (24 h) On the spatial scale, flexible resources cannot move freely
State dependency	Both flexible supply and demand are strongly correlated with system state	Regulation of conventional units and energy storage is related to their output level and historical state. Flexibility requirements are related to load levels, renewable energy output and other conditions
Bi-direction convertibility	Under certain conditions, flexible supply and demand can be converted to each other	Demand response, wind/solar power curtailment, etc.
Probabilistic characteristics	Necessary to build a framework for uncertainty analysis using probabilistic methods	Use random variables to describe flexibility

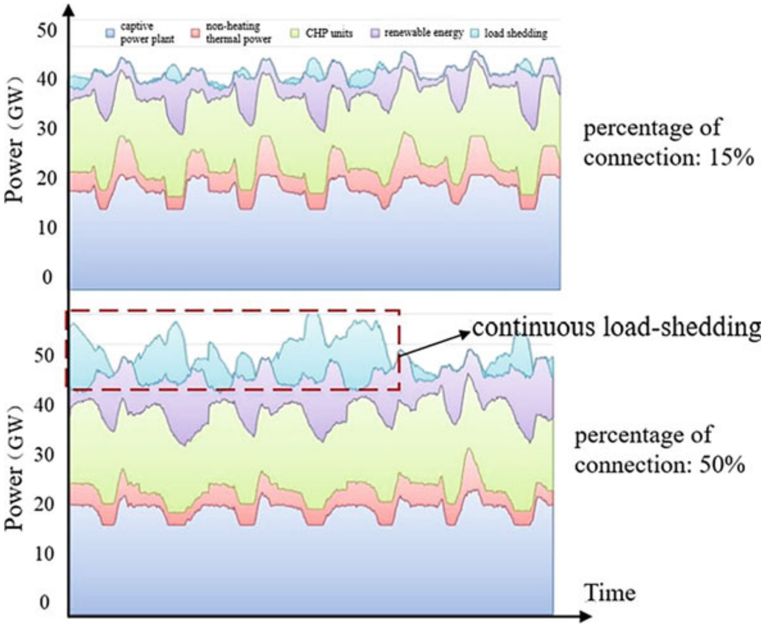


Fig. 4.23 Flexibility issue brought by high share of renewable energy

a great damper on the healthy development of renewable energy and energy reform at large.

Figure 4.24 reveals a typical day of power balance after a high proportion of wind power is connected to the grid. The green area represents the traditional load operation scenario without renewable energy; the purple shows the net load (difference between

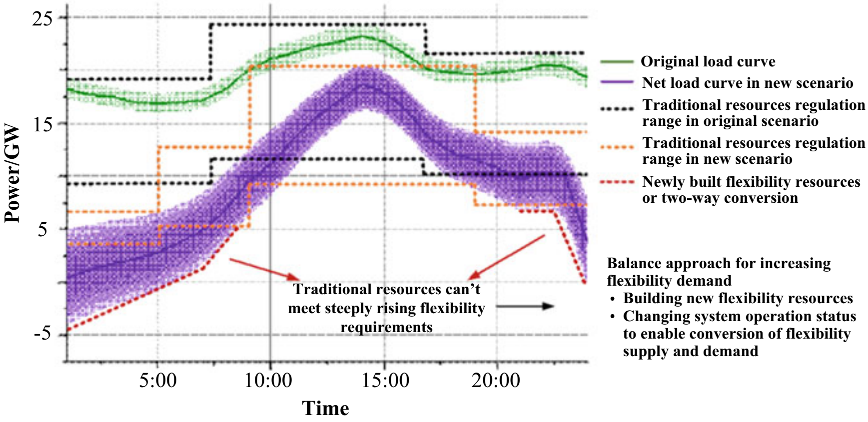


Fig. 4.24 Diagram of flexible balance of supply and demand in power system

load and new energy output) operation scenario with a high percentage of renewable energy in the grid, and the shaded part means the uncertainty range. In this case, if the traditional operation mode is still being used, load shedding will occur in multiple timeslots, as shown in the red dotted line in the figure, which not only reduces the economic efficiency of power system operation, but also impedes healthy development of renewable energy.

When a high uptake of renewable energy is fed to the grid, three obvious changes emerged: (1) Steep ramping in the system was found at certain timeslots, widening the peak-valley gap, which means a substantial increase in flexibility demand; (2) Renewable energy replaces most of traditional units output, thus reducing the regulation capacity of conventional power supply (flexible supply); (3) The failure of the traditional power balance mode means the output range of traditional power supply can't completely cover the net load area, resulting in inflexibility at certain timeslots, and a subsequent load shedding or loss of renewable energy. The current operation rules of power system put safety at the center, thus leaving no choice but load shedding. Under this circumstance, in the future when a high proportion of renewable energy power is fed to the grid, the coordinated development of generation, grid and load based on flexible balance will be inevitable.

Power flexibility measures mainly include five aspects: power flexibility transformation, energy storage, demand response, power grid expansion planning and flexibility market mechanism. The first four seek to improve flexibility from the technical perspective; the last one aims to incentivise flexibility from a market point of view. IRENA conducted a study on the cost of flexible resources for a multi-energy system, and the results are shown in Fig. 4.25.

Now, varied measures in generation, grid, load and storage of China's power system have been actively deployed, with fruitful results. Some parts of northern China have conducted flexibility modification of thermal power units, demonstration of large-scale energy storage in power grid, and ultra-high voltage direct currents project, among others. Jiangsu province has piloted demand response and coordination of generation, grid and load, alleviating wind and solar curtailment to some extent. But it should be noted that renewable power at the present still accounts for a small percentage in the grid. Should it continues growing to extremely high proportion (e.g. 80% or even 100% at certain timeslots), the power system will be troubled by close to zero or even negative net load. Due to the volatility of renewable energy output, the resource potential to solve flexibility problems within the power system will reach its limits. Therefore, in order to further reduce wind and solar curtailment through flexible resource planning in a more economic, efficient and holistic manner, and accommodate the future high uptake of renewable power in the grid, other forms of energy system should be introduced. The integration of other forms of energy and electricity should be utilized to study the way multi-energy integration improves system flexibility based on their physical mechanism. By doing so, the flexible balance of supply and demand of the power system could be addressed in the broader context of energy system, which would enable the move towards the electricity-predominant new generation of energy system—the energy internet.

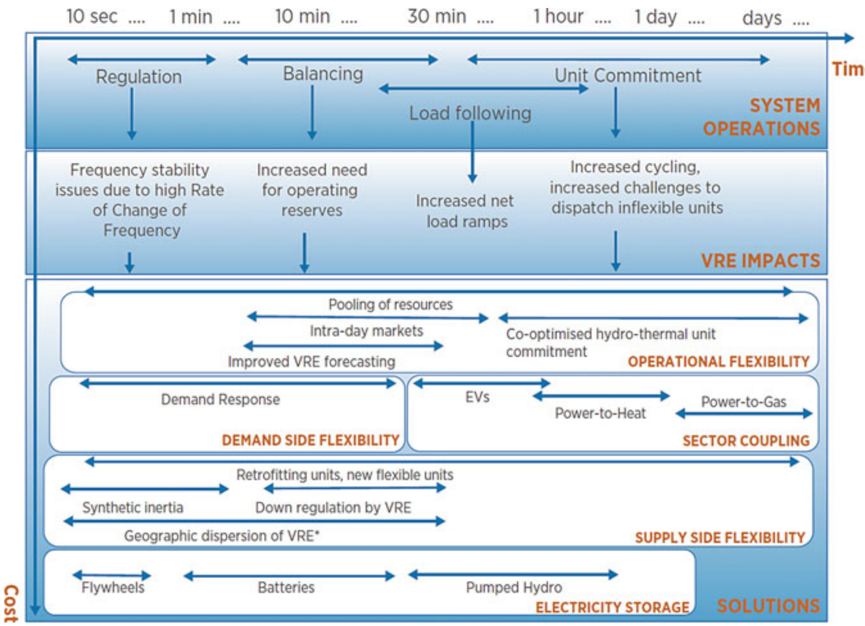


Fig. 4.25 Comparison of various flexible resources in an integrated energy system based on scale of cost and time

4.5 Policies and Recommendations for Expediting Transition of China's Power System

1. **The sustainable development of renewable energy should be underpinned by a range of policies in order to achieve a high share or even 100% scenario.**

(1) **Build auxiliary service power markets to support the flexible modification of thermal power units.**

Flexibility modification of thermal power units represents a relatively low cost solution with mature technology. But it must be supported by auxiliary service electricity market. Therefore, it's a must to build a stronger national auxiliary service power market. Pilots could be conducted in provinces where renewable energy develops well.

(2) **Accelerate the building of a new generation of energy market system that is unified, open, competitive, orderly and coordinated.**

It is important to continue to deepen reform of the power system, coordinate medium-and-long term trading of power with spot trading, and actively promote new trading methods such as green certificates for renewable energy and carbon emission rights. At the same time, establishing multi-shareholder comprehensive energy investment and operation enterprises to provide users with efficient and integrated energy services is necessary. China is actively advancing a new round of power system reform. Currently, many regions have tried out the power spot market and renewable energy green certificate trading, which unfortunately are still in the infant stage and lacks coordination. Meanwhile, the management on electricity, gas, oil, heat and other market is still fragmented without comprehensive planning. It's advised to advance the reform of the power system, achieve the coordinated operation of medium-and-long term power trading and spot transactions, open the channel of private investment, actively establish a comprehensive energy service system, and encourage all types of energy enterprises to participate in the development of the new generation of energy market.

(3) **Learn from the success stories of Europe and the United States, facilitate the establishment of demand-side management in China, which should go hand in hand with power market reform.**

Demand response technology is essential to accommodate the high uptake of renewable energy in the future. Now, China still lacks full-fledged market mechanism, and pilots in this regard have been mainly carried out in Beijing, Shanghai and other developed areas, with limited technology demonstration and scale-up. It's important to strengthen and expand demonstration efforts, coupled with market pricing policies. The key step is combining demand response with the "green tariff" system. In the consumption tarrif, markup of the new energy development fund should be moderately increased, and cross-subsidies for residential electricity from industry and commerce should be reduced or scrapped. The low electricity price for residential use is the leftover of the low wage system in past, which has long been divorced from the national conditions, and has led to energy waste. "Green tariff" ensures timely payment of new energy subsidies and boost green energy development. Other measures include: to curb high consumption of electricity to save energy and power, and improve energy efficiency through multi-energy complementary measures; to reduce electricity price of industry and commerce to enhance competitiveness of Chinese products and economy; and to provide subsidies to low-income earners to ease the financial burden of power consumption.

(4) **Develop highly efficient, low-cost, long-life energy storage technologies and products for widespread application.**

A high uptake of renewable energy is the salient feature of the future power system. All forms of energy storage devices (electricity storage, heat storage and hydrogen storage) can be used by power grid and users to contain the fluctuation and intermittency of renewable energy output, meet the stability and economic demands of distributed energy supply, and support the development of electric vehicles.

The following efforts are supposed to make: to strengthen basic research on energy storage, with emphasis on supporting the development of advanced battery energy storage materials with high energy density and low cost (e.g. grapheme), and research on improving safety and reducing negative environmental impacts; to explore the research and application of high energy density and low cost energy storage technologies such as metal aluminum air fuel cell; to carry out project demonstration and pre-commercialization support, and focus on building large-scale, high-performance, and highly reliable energy storage systems; to provide financial support for the early market players of new business models, so that emerging energy storage technologies and their operation models can be quickly introduced into the market; to reinforce supervision on the operation of energy storage power stations and enhance the market mechanism of energy storage application; to develop a sound pricing and compensation strategy to increase benefits to energy storage providers for their role in system regulation and auxiliary services; to offer economic compensation for user-side distributed energy storage; to put in place a robust medium-and-short term power market mechanism, increase market openness, and encourage competition and emerging market models; to channel private investment into energy storage development, and streamline the financing procedure of new and large storage systems.

2. **Multi-energy complementary and integrated development should start with the convergence of electricity and heating, which represents the crucial first step towards the vision of the energy internet.**

(1) **Facilitate the clean and efficient development of summer air conditioning and winter heating in central China to meet the increasing demands of urban and rural residents for living comfort.**

As China prioritizes its northern region for promoting clean and efficient winter heating, tailor-made efforts should also be made to target the vast central region to scale up individual or centralized air source, ground source heat pump together with sunlight, heat storage and other efficient and clean approaches of air conditioning and heating by harnessing state-of-the-art technologies and economic incentives. Where conditions permit, distributed solar power generation could also be combined. The sole dependence on traditional air conditioner leads to highly concentrated load in summer and poor comfort and low energy efficiency in winter. This must be changed to meet the pursuit of urban and rural residents for a better life.

(2) **Prompt energy-intensive industrial enterprises to strengthen energy conservation and multi-energy complementation.**

The improvement of end-use energy efficiency contributes the most to the overall efficiency of the energy system. It's advised to carry out in-depth investigations into various energy use in enterprises and put forward suggestions on technological measures and policy incentives. Existing studies have shown that it's most effective to realize multi-energy complementary use of coal, gas and electricity and recycling of waste heat within large enterprises. But policy measures, including promoting win-win cooperation between energy sectors, as well as finance and taxation, need to be formulated through further investigation and research.

(3) **Intensify R&D and industrialization of key technologies and equipments to provide technical support for building China's energy internet.**

The first is the new generation of power electronic materials, components and power electronic equipment technology and equipment based on wide band gap semiconductor. With the extensive access of renewable energy to the grid, the new generation of power system will be characterized by the high proportion of power electronic equipment. Built on the wide band gap semiconductor, the new generation of power electronic equipment boasts high temperature resistance, high voltage and overload capability and high reliability. It's currently under research and development for small-scale pilot production at home and abroad. It's therefore suggested that R&D and development should be strengthened for the new generation of power electronic materials (e.g. silicon carbide), devices and equipment to boost the development of a new generation of power system and the transformation of smart grid.

The second is the gas turbine power supply for distributed energy as well as technology and equipment for the comprehensive utilization of energy. China's distributed energy equipment is relatively underdeveloped. In particular, small and medium-sized gas turbines that use natural gas for power generation with waste heat utilization in the country mainly depend on imports, with technologies monopolized by developed countries in Europe and America. It's advised to boost R&D research to support the development of distributed natural gas turbine.

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Chapter 5
Reality and Challenges of China's Water Resources Management in the Context of Climate Change

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Abstract Water is a fundamental and essential resource for sustainable and healthy development of natural environment and human society. China boasts considerable water resources but is below world average on a per capita basis, and is challenged by the disparity in temporal and geographical distribution and poor utilization of water resources, severe water pollution, etc. As water is closely associated with climate change, change in water resources amid climate change in the future might affect China's water security. Based on the reality and challenges of China's water resources, this chapter shall discuss the evolution of China's water management system and the current water demand, as well as the trend in future. Next, a study of water resources risk and its temporal and spatial distribution in China's power industry are introduced, concluding with policy recommendations for China to address the challenges.

Keywords Water resource · Water demand · Distribution · Water management

5.1 Reality and Challenges of China's Water Resources

5.1.1 Reality of China's Water Resources

According to World Meteorological Organization and UNESCO, water resource is defined as water that is suitable for use or of potential use to humans. For China, usable water resources mainly include river runoffs and underground water, most of the former coming from precipitation. Based on annual bulletin on water resources

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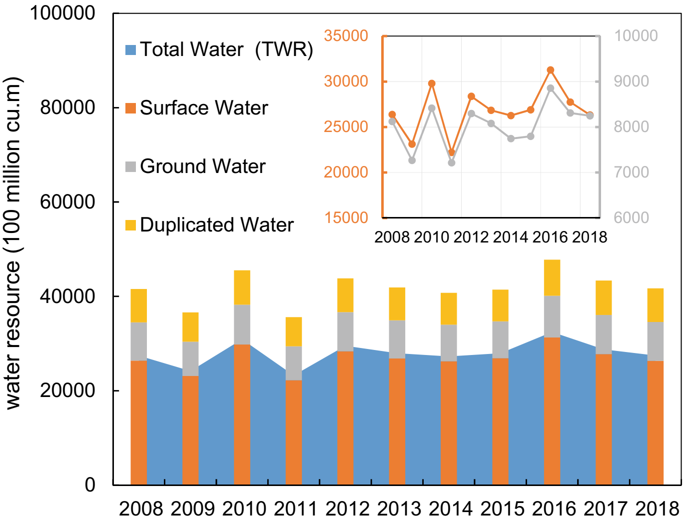


Fig. 5.1 The composition of water resources and its evolution of China in 2008–2018

in China published by the Ministry of Water Resources, fluctuations were observed in the total water resources in China within the decade (2008–2018), with the annual average standing at 2800 billion m^3, compared to underground water, surface water remained the principal part of China's total water resources, accounting for 96% on average throughout the years (Fig. 5.1).

China ranks the sixth in the world with 7% of the world's total fresh water, yet the pressing challenge of shortage in fresh water has become a major impediment for China's sustainable economic and social development. Statistics from World Resources Institute suggest that China is home to 20% of the world population yet possesses only 7% of global water resources, meaning that water resources per capita represents approximately one quarter of the world's average. Currently, 16 out of 31 provinces in China's mainland are plagued by water shortage, while two thirds of the 600 cities face severe water shortage. China, as one of the main countries struggling with water resources depletion, has no choice but to confront and tackle this challenge.

Another key feature of China's water reality is the disparity in temporal and geographical distribution, as can be described as "abundance in the south and shortage in the north; abundance in summer and shortage in winter", shaping varied endowments in different regions. The socio-economic growth has prompted a growing need of water. Since 2010, total water consumption in China has remained above 600 billion m^3 and the demand for water has hit a high level, exceeding 20% of total water resources, which has presented a daunting challenge for the rational and balanced exploitation and utilization of water resources.

Apart from shortage and disparity, water resources in China are also troubled by the grim reality of deteriorating quality due to pollution from industries, urban life, non-point source pollution of farmland, acid rain and poor reuse. Factual statistics published by the World Resources Institute revealed that nearly one third of the ten major river systems in China suffer from poor water quality; while 60% of the underground water monitoring stations indicate severe pollution. The *2018 Water Quality Assessment of Waterhead Areas in China* published by Public Environmental Research Center in 2019 showed that pollutants exceeding standards were detected in 251 waterhead areas in 110 prefectural cities/counties under provincial administration in 27 provinces in 2018, of which 107 waterhead areas were found to exceed the pollution standards in all samplings in 2018, including 81 underground water sources and 26 surface water sources; 32 of these water resources were at prefectural level or above while 75 were at county level. The grave water pollution has made water environment governance an urgent task for the country.

Fortunately, China has scored initial success in protecting water ecological environment with stricter water resources management and continued progress in the battle against water pollution. Statistics released by the Ministry of Ecology and Environmental indicates that in 2019, 74.9% of the 1940 surface water monitored sections were rated as good water quality, up 3.9% points year-on-year; 3.4% of the controlled sections were worse than Grade V, down 3.3% points from the same period of the previous year. Efforts in tackling water pollution have been redoubled in recent years while the economic growth model at the cost of water environment is gradually reversed, which signals increasing quality-oriented development. However, unbalanced and poorly coordinated water environment protection remains a prominent issue, and quality improvement of water resources still requires an uphill battle.

5.1.2 Trends of Change and Variation of Temporal and Geographical Distribution of China's Water Resources

According to the study of (Li et al. 2014), during fifty-five years from 1956 to 2010, China's total renewable water resources remained at an annual average of approximately 2.755 trillion m^3, with annual fluctuations around the average due to inter-annual variation in climate conditions (Fig. 5.2). The change of China's total water resources was insignificant with a slight increase during the past 55 years from 1956 to 2010, while mere 1% of increase of annual water resources in the last 20 years compared to historical average value. Nevertheless, the inter-annual variation within the 20 years from 1991 to 2010 showed a tendency of growth as compared to the annual average from 1961 to 1990, and such inter-annual fluctuation has not abated in recent years. Within the 55 years, the records in most years varied about 1 ± 10% compared to the average. There are 9 years experienced a fluctuation between 10 and 20%, while one year (1998) witnessed an 20% excess of the average.

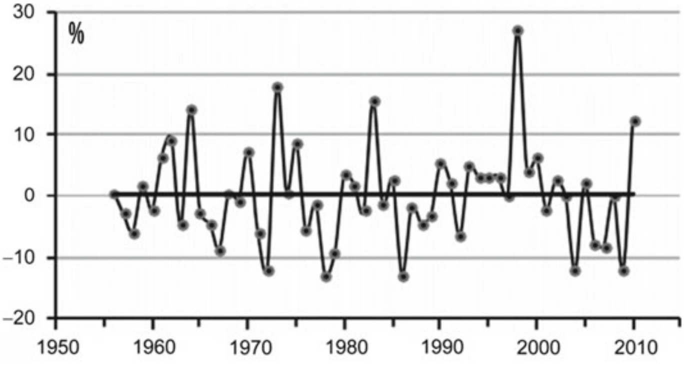
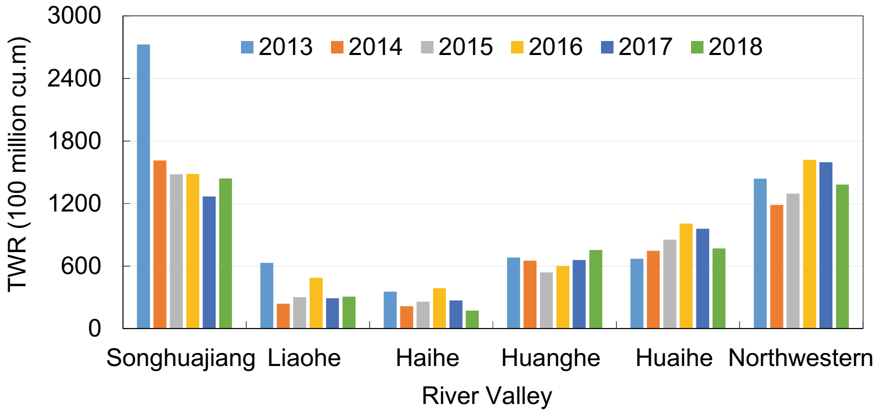


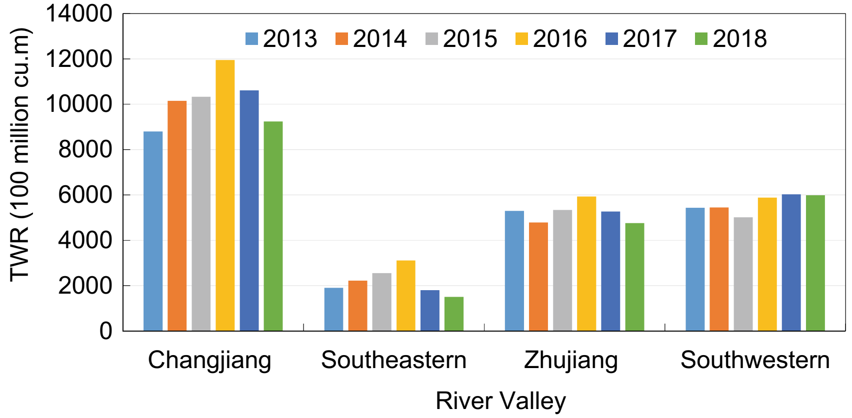
Fig. 5.2 Inter-annual relative variation of China's total water resources

Though the variation appears insignificant from a national perspective, considerable disparity among regions remains a reality, which could be described as "abundance in the east and shortage in the west" and "abundance in the south and shortage in the north". Among the ten Level I water resources regions in China, 6 are in northern China and 4 in southern China; the former include Songhuajiang River region, Liaohe River region, Haihe River region, the Yellow River region, Huaihe River region and Rivers in northwest while the latter include Yangtze River region, Rivers in southeast China, the Pearl River region and Rivers in southwest China. According to 2018 China Water Resources Bulletin, the six regions in the north account for merely 21.15% of the country's total quantity of water while the four regions in the south make up 78.85% (Fig. 5.3). 83% of China's water resources are concentrated to the south of the Yangtze River Basin, while north China features relatively arid climate with only 17% of water in China but is home to 41% of the population and 56% of the arable land. In 2018, the water resources per capita in the ten provinces with the most abundant water resources were 62 times that of the ten provinces least abundant in water. Most provinces on the top ten list are mainly located in southwest and southeast China with less developed economy; while the bottom ten were mostly northern provinces with developed economy. The regional disparity in economic growth is as distinctive as in water availability but in reverse order (Fig. 5.4).

Besides inter-annual variation, dramatic disparities are also observed among different regions within the same year. Inter-annual variation is relatively small in the south such as the Yangtze River region, rivers in the southeast, the Pearl River region, rivers in the southwest, northwest as well as northwest river basin, and is more distinct in Songhuajiang River region, Liaohe River region, Haihe River region, the Yellow River region and Huaihe River region. In Huaihe River region, the year with the most violent fluctuation recorded over 100% deviation from the annual average. Due to seasonal precipitation in different river basins, surface water distribution within the year varies as well. To illustrate, rainfall in north China peaks during summer, autumn because of summer monsoon, with summer accounting for over 60% of the



(a) The river valley in north China



(b) The river valley in south China

Fig. 5.3 The total amount of water resources of China river valley in 2013–2018

annual precipitation, while in northwest China, over 50% of the annual precipitation takes place in summer, and winter precipitation represents a maximum of 10%.

In terms of future trend of water resources, a study by Wang and Long (2016) predicts an increase in annual water resources in north China and northeast China and a certain drop in southern provinces; in view of more frequent extreme weather events, the seasonal variation of water resources is likely to rise, posing a major challenge to the rational utilization.

The changing trend of China's water resources may be encapsulated as follows: the total quantity of water resources fluctuates around the annual average, with more dramatic inter-annual and seasonal variations between regions. Amid rapid socio-economic development and growing demand for water, variations in temporal and

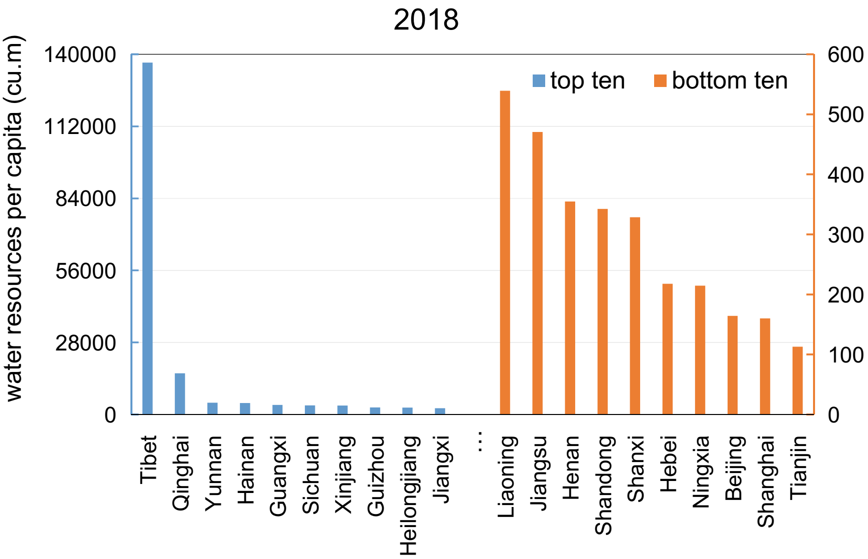


Fig. 5.4 China's top 10 and bottom ten provinces of the total water resources per capita in 2018

geographical distribution constitute a challenge to rational and efficient use of water resources.

5.1.3 *Water Resources Management Policies in China*

5.1.3.1 Evolution of Water Resources Management System in China

A key solution to addressing the daunting challenge of water shortage is to step up the management of water resources for sustainable water utilization, while the creation of a stringent and well-structured water management system shall provide the safeguard for effective management of water resources. According to the evolution of water protection and utilization in China sorted out by Xia et al. (2016), Jia and Zhang (2011), China's water resources management system has undergone the following four stages:

(1) Absence of proper resource management with a sole focus on engineering projects rather than resources (1949–1977). Water management in China during this period was fragmented, as the Ministry of Water Resources was only responsible for water conservancy efforts that mainly includes flood prevention and water diversion across river basins; while hydropower, urban water supply and inland navigation fell under the responsibilities of the Ministry of Fuel and Industry (Ministry of Power), the Ministry of Construction and the Ministry of

Transportation respectively. Even farmland irrigation and water conservancy, which is understood as a typical branch of water conservancy, used to be managed by the Ministry of Agriculture over a considerable period.

(2) The infancy of institutional management predominantly built on administration mandates (1978–1987): as water shortage made water resources management an actual need, this period was mainly characterized by water engineering project construction and water resources development. However, as the Ministry of Water Resources lacked the functionality and legitimacy of water management as an administrative organ in water-related affairs, conflicts among provinces and cities in water usage had to be mediated by the State Council, which mapped out plans for water sharing for certain river basins and water supply projects through administration mandates. As production was subject to national plans in a planned economy, it was only natural that conflicts in water use were handled via governmental mandates.

(3) Introduction of a water withdrawal permit system (1988–1998): the promulgation of the Water Law of the People's Republic of China in 1988 unveiled a new stage of water management in China where the focus shifted towards comprehensive utilization of water, aiming at harmony between man and water. As per the Water Law, a permit was obligatory to withdraw water. *Administration Regulations on Water Withdrawal Permit and Water Resources Charge Collection* issued by the State Council in 1993 granted water management an independent position from engineering management with its specific legal basis.

(4) Regular institutional management based on water right (2002–): the revised Water Law took effect in 2002, which sought to preserve water ecology and build eco-civilization. The new Water Law put in place the water assessment system, stipulating that plans for national economy, social development, overall urban development, and key construction projects must fit in with local water conditions and flood prevention requirements and be approved through scientific assessment; it also provided that the size of a city, industries, rural projects and services involving significant water use should be constrained in regions lacking water resources. The emergence of water assessment system has provided the institutional safety net for the lead-time and scientific evaluation on water management of plans and projects.

5.1.3.2 The "Three Red Lines" in Water Resources Management

The No. 1 Central Document of 2011 explicitly stated that the strictest water management regulations shall be implemented with "three systems" put in place, i.e. total water consumption control, water efficiency control and water pollution limit in water functional zones, thus drawing the "three red lines", i.e. total water consumption, water efficiency and pollution load limit in water functional zones. Such regulations were followed by *Opinions of the State Council on the Implementation of the Strictest Water Resources Management Regulations* published in 2012 to confront the mounting water challenge. This document, commonly known as "Three Red Lines", identified the following goals:

(1) To determine the red line for water resources exploitation and use, with a strict cap on total water consumption. By 2030, China's annual water consumption shall be kept under 700 billion m^3. The Document stated that the focus of water management should move from water supply management to water demand management. Water distribution plans of major river basins should be executed and targets for total water withdrawal should be created respectively at catchment, provincial, municipal and county levels.
(2) To determine the red line for water efficiency control and put a resolute stop to water waste. By 2030, water efficiency in China should reach or approach the top level in the world with water use per 10,000 yuan of industrial output (at constant price of 2000, same hereinafter) down to below 40 m^3, and effective use coefficient of farmland irrigation water increased above 0.6.
(3) To determine the red line for pollution limit in water functional zones. By 2030, the discharge of main pollutants into rivers and lakes should be controlled within the environmental capacity of water functional zones, of which over 95% should measure up to water quality standard.

Since the earnest implementation of the strictest water management regulations and the issuance of the "Three Red Lines", China has made steady headway in water quality improvement and instituted *Action Plan for Water Pollution Prevention and Control*. By 2018, water environment in China saw an upgrade in various dimensions, reversing the trend of growing water pollution across the country. According to *2018 Bulletin on Ecological Environment of China*, 1009 black and foul water bodies in 36 key cities were eliminated or largely eliminated, accounting for 95% of all such areas; 99.9% of 6251 problems observed in 1586 water resources were solved.

5.1.3.3 Trend of Water Resources Management

With water management regulations and measures gradually taking shape and strengthened, new demands for water utilization and protection have emerged amid greater attention to eco-environmental protection and the pursuit of green development. From the implementation standpoint, the future trend of water resources management includes:

(1) Encouragement of eco-economic management: a stress on water-efficient economy, i.e. enhancement of water use efficiency on top of more effective water use management.
(2) Creation of a unified water management system: a holistic approach shall be adopted for the scientific and comprehensive utilization of water resources. A unified authority for water management shall be created for coordinated use of water resources, while ensuring more appropriate use of funds and more rational industrial footprint.

(3) Increasingly market-based water management: water is of infinite value, yet the use of water incurs cost; so water use shall follow the law of value. The entire process of water supply consists of withdrawal and transportation in the earlier phase, maintenance and management in the later phase and the disposal and reuse of wastewater. Currently, water is cheap in China, resulting in the transfer of profits from water suppliers to water users. The low price, in some measure, has led to depletion of underground water and hampered control of surface and underground water pollution, and has failed to incentivize industrial sectors to proactively curb water pollution or reuse industrial sewage, hence the commonplace of water waste in enterprises.

(4) Establishment of a water-saving society: campaigns are now underway in many parts of China to build a water-saving society, especially in the north. The outgrowth of social development, a water-saving society involves maximum economic and social benefits of water resources and the subsequent creation of material abundance and a pleasant ecological environment.

(5) Adoption of advanced technologies to empower water management: advanced technologies in this regard mainly refer to computing technology, remote sensing and communications, the application of which represents a basic trend of water management. The water resources management system built upon computing technology, including mathematical modeling for various purposes, GIS and MIS, etc., has made enormous contribution to water management. Now, GIS, MIS and related auxiliary systems in water resources have been launched in many developed countries with the aid of computing and remote sensing technologies, and have reaped fruitful results. Such success stories can be learned for more effective water management in China.

5.1.4 Water Challenges in China

The availability of total water resources in China features considerable regional variation and remains a stumbling block for some regions. Though no major changes are observed in total amount of water in recent years, some regions are being challenged by a sharp drop in water availability and greater inter-annual fluctuations, which might have worsened water shortage in these areas in certain years. Meanwhile, regions suffering from inherent water shortage are still constrained by water availability. Examples can be found in the northwestern river basin in the arid climate zone, where the increasing water resources during the last 20 years cannot override its dry climate conditions as the aggregate increase remains limited. Besides, the geographical distribution of water resources in China will not be essentially transformed with the influence of future climate change, and the seasonal variation will widen as extreme climate events increase. In general, inadequate availability in certain regions and uneven seasonal distribution will pose challenges for meeting the need and ensuring appropriate use of water resources.

China still faces an uphill battle of tackling water pollution with prevailing eutrophication, excessive organic pollutants, salinization, etc. in water bodies such as rivers, lakes, reservoirs and underground water. In 2018, water quality of 18.4% of rivers, 75% of lakes and 12.7% of reservoirs were Grade IV or below, which can't be used directly in socioeconomic activities without treatment. The treatment of polluted water bodies requires tremendous investment and strenuous efforts over a long period.

China's basic management of water resources remains fragile. Despite the striking progress made in the water management system through continuous adjustment, problems due to the previous obsession with economic growth still exist, such as lack of control of both quantity and intensity of water consumption and challenge in capping total pollution in water functional zones. The water management system calls for continuous improvement with growing demand from the economy and society for green development.

5.2 Current Water Demand and Its Trend in China

5.2.1 Current Water Demand in China

Water is one of the essential material resources for the survival of human beings, with a direct bearing on social life and economic development. The reform and opening up has ushered China into a fast track of socioeconomic progress as China's GDP in 2018 exceeded 90 trillion RMB, up from 454.5 billion RMB in 1980. During this period, water demand in China jumped from 443.6 to 601.6 billion m^3. While growth in agricultural water consumption moderated, industrial and domestic water demand soared. From 1980 to 2018, the proportion of agricultural, industrial and domestic water use in total water consumption has undergone a shift from 83.4%, 10.3% and 6.3% to 61.4%, 21.0% and 14.3% respectively in 2018 (3.3% of the water consumption in 2018 came from eco-environment water replenishment by human intervention).

The surge in water demand driven by the phenomenal socioeconomic development in China has made water resources an increasingly prominent issue, and the probe into the correlation between economic growth and water demand is gradually becoming a key topic for academic research. Studies have shown that economic development, industrial structure and national income have dramatic impact on water demand (Lei et al. 2017). To illustrate China's current socioeconomic development and the effect of economic growth on water consumption, four economic indicators (GDP, output of the primary industry, output of the secondary industry, GNP) and four water consumption indicators (total water consumption, agriculture water consumption, industry water consumption and domestic water consumption) were chosen for this study. Figures 5.5 and 5.8 reveal China's economic development over 15 years (2004–

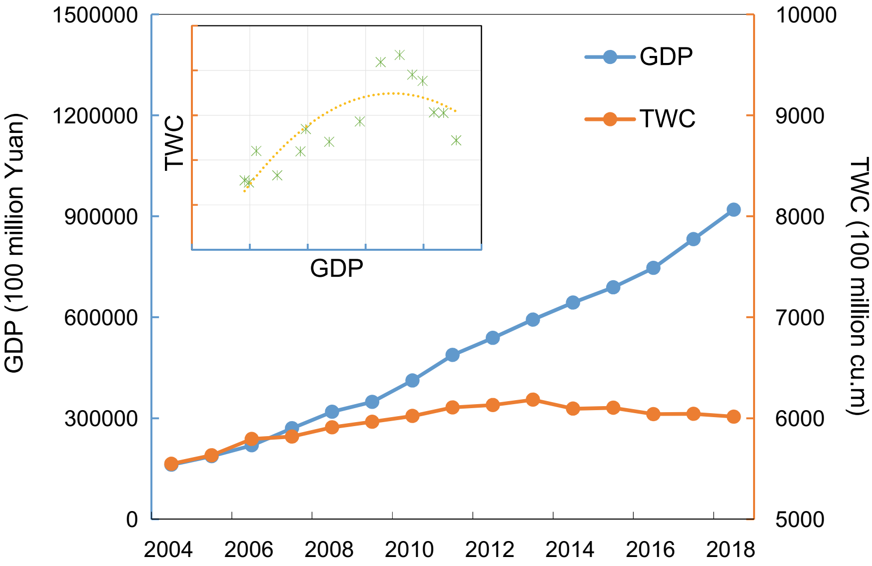


Fig. 5.5 The evolution of GDP, total water consumption (TWC) and the nexus between them

2018) and the linkage between socioeconomic growth and water resources (Figs. 5.6 and 5.7).

According to Fig. 5.5, in contrast with the impressive GDP growth that captures world attention, the changes in total water consumption in China has remained rather flat, registering a steady increase until 2012 when the curve started to flatten. The divergence between water use and economic growth indicates a decrease in water consumption per 10,000 RMB GDP and continues improvement in water efficiency in China, which is consistent with the conclusion by Ma and Tao (2017). It should be noted that evolution of the output of the primary industry and agriculture water consumption and that of the output of the secondary industry and industrial water consumption, as well as the respective links between them (Figs. 5.6 and 5.7) largely echoes that between GDP and total water consumption; yet the surge in the output of the primary industry is gradually flattened while the momentum for the secondary industry remains strong. On one hand, it indicates that industry has remained a key engine for economic growth during the past 15 years; on the other hand, it means that water efficiency of agriculture and industry is constantly improving. Another interesting fact is observed in the evolution of national income and domestic water consumption (Fig. 5.8). From 2004 to 2018, the spike in national income was accompanied by both sustained improvement in living standards and continuous rise in domestic water consumption and the fitting result is manifested as close to linear growth, meaning that the increase in income and living standards would significantly boost domestic water consumption.

In fact, China's water efficiency has long been a focus in academic research. Take the study by Liu Jing et al. as an example, an analysis of water quantity and

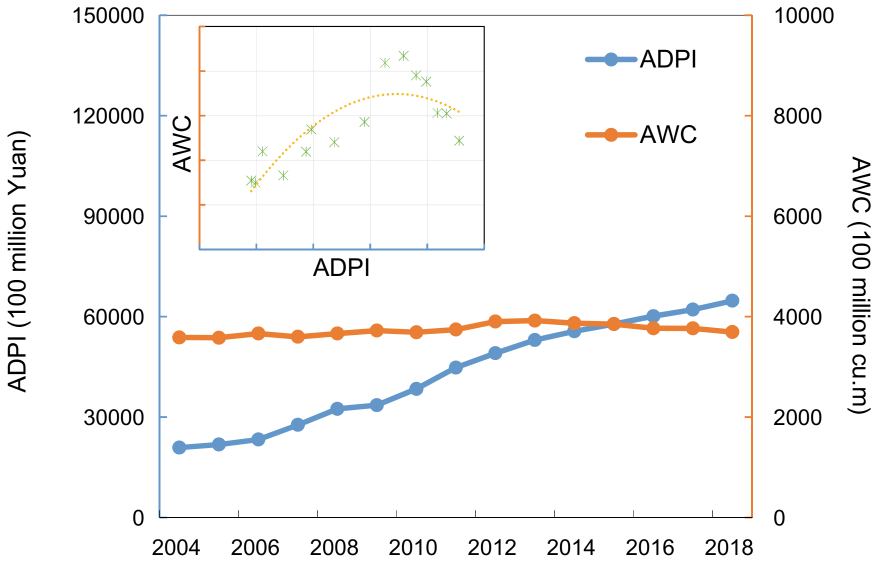


Fig. 5.6 The evolution of added value of primary industry (ADPI), agriculture water consumption (AWC) and the nexus between them

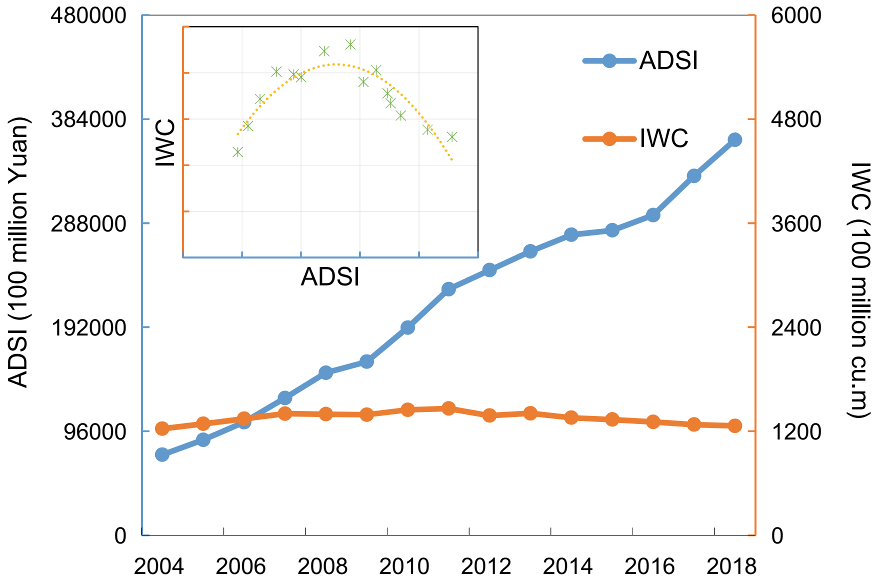


Fig. 5.7 The evolution of added value of secondary industry (AVSI), industry water consumption (IWC) and the nexus between them

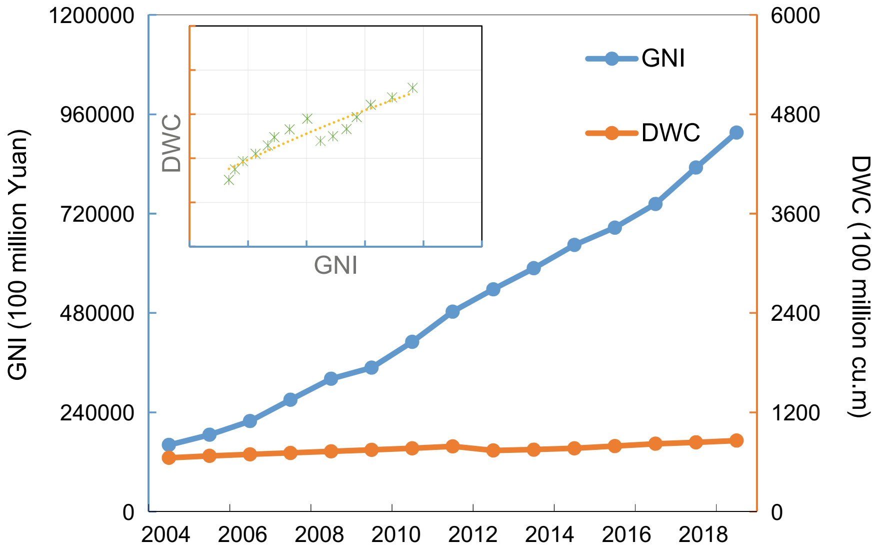


Fig. 5.8 The evolution of GNP, domestic water consumption (DWC) and the nexus between them

consumption data in 10 Class 1 water conservation zones between 1997 and 2016 indicates considerable room for improvement in China's water efficiency compared to top-ranking countries (Liu et al. 2019). Industrial water efficiency is found to be slightly below the world's average but higher than the US where industrial production also makes up a large chunk of economy. However, utilization of irrigation water in China is merely 46% compared to 54% in the US and 87% in Israel, which signifies a large gap between China and top-ranking countries.

As is mentioned in the previous section, despite the abundance of total water resources in China, their distribution is characterized by significant temporal and geographical variation. Decades of economic take-off have spurred the demand for water, which in turn brought mounting water consumption and aggravating water shortage. Over one third of land in China is under high or extremely high pressure for water resources, which means the growing demand for fresh water has set a higher bar on the supply of renewable water resources. To put China's water pressure into perspective, World Resources Institute conducted an analysis of the base pressure of nationwide water use with three years of water consumption data (2001, 2010 and 2015). The analysis by Wang and Long (2016) concluded that the degree and spatial distribution of water use pressure in China were basically consistent in 2001, 2010 and 2015, with lower pressure in southern China and mid-to-higher pressure in most northern regions.

5.2.2 Major Industrial Drivers of Water Demand in China

As is illustrated in the trend of water consumption by industry in Fig. 5.9, from 2010 to 2018, no major changes are detected in total water consumption in the agricultural sector, which stayed close to 350 billion m^3 with a mere annual increase of 0.01%; the industrial water consumption showed a slight drop with an annual increase of −1.7%; domestic water consumption saw a visible increase with an annual growth of 1.5%. This means that despite agriculture being the largest water consumer, domestic use was the inherent driver for rising water demand in the last decade.

By province (Figs. 5.10 and 5.11), water demand is higher in Jiangsu, Xinjiang, Heilongjiang, etc. and lower in Beijing, Tibet, Qinghai, Tianjin, etc. In 2018, agriculture remained the largest source of water demand in most provinces. Yet for economically developed eastern regions such as Beijing, Shanghai and Jiangsu, domestic use has far outstripped agriculture as the biggest water consumer. Take Beijing as an example, the agricultural sector accounted for less than 20% of total water consumption in 2018, while domestic use took up over 70%. In general, the mix of water demand of provinces in China is closely linked to their economic development and industrial structure. In economically developed regions, industry and services tend to outshine agriculture, hence a smaller share of the latter in water consumption and domestic use the main source of water demand. For less developed provinces where agriculture remains a major economic driver, the percentage of agriculture is higher in total water consumption as.

In fact, many researchers in China and abroad have estimated and predicted the sectoral mix of water demand in China. Shen (2005) has estimated the amount of

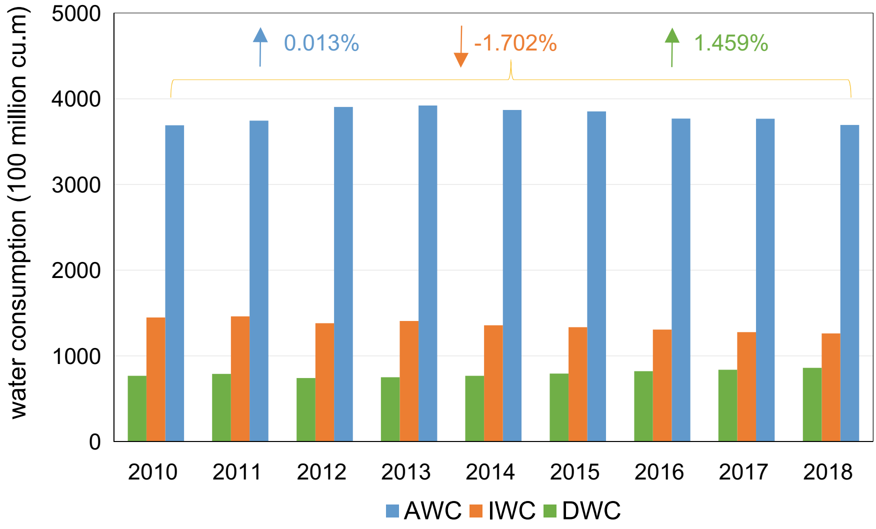


Fig. 5.9 The composition of China's water consumption

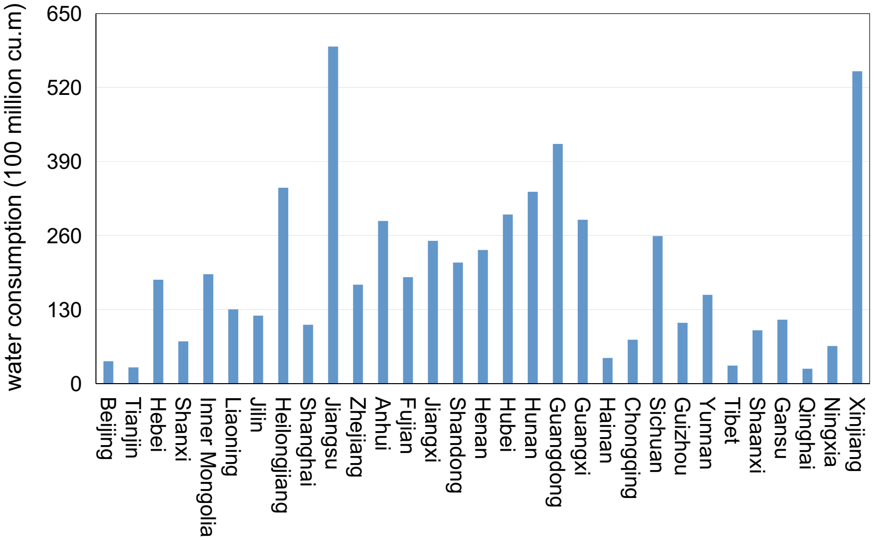


Fig. 5.10 The total water consumption of Chinese provinces in 2018

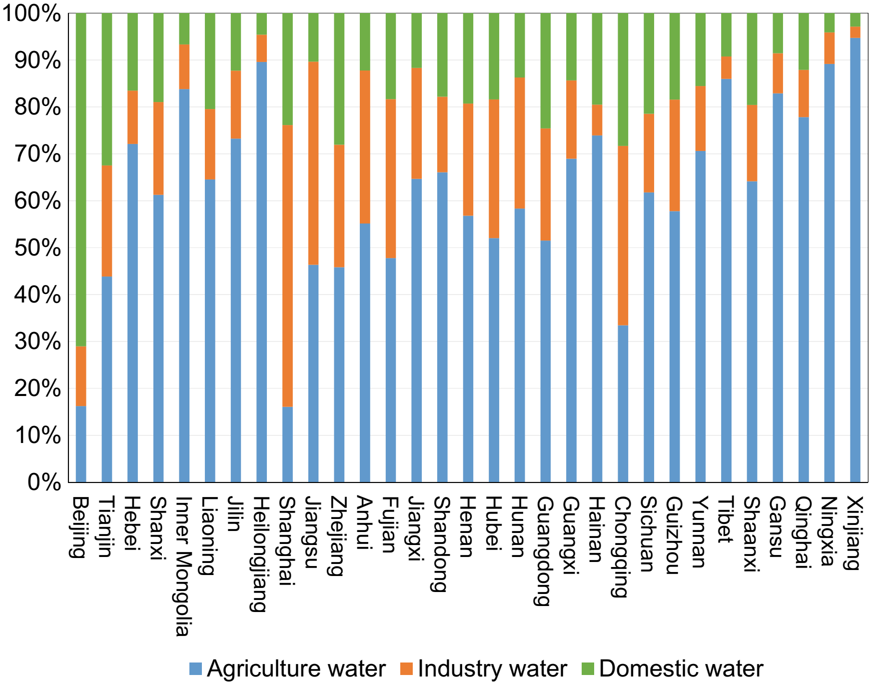


Fig. 5.11 The composition of Chinese provinces' water consumption in 2018

water needed by industry, agriculture, domestic use and ecological environment in 2030 and 2050 by measure of future China GDP, population, industrial structure, urbanization growth, etc. At the current momentum, total water consumption is expected to hit 727.7 billion m^3 (2030) and 786.3 billion m^3 (2050), of which most of the increase comes from industry, domestic use and ecological environment. Chai (2012) has made a forecast of agriculture water demand in six provinces and municipalities in north China by 2015 based on gray model, warning that agricultural sector in Hebei Province would suffer a shortfall of 4.62 billion m^3 in 2015.

For more detailed description of the inherent drivers of water demand in China, some studies have probed into water demand in specific industrial segments. For instance, Wang et al. (2014) identified the industrial water footprint and its intensity through quantitative accounting, concluding that agriculture, food and tobacco processing, power and heat production and supply ranked relatively higher in full water footprint, of which agriculture took up 77.7%, 79.0% and 79.3% in 1997, 2002, 2007 respectively, and the production and supply of power and heat accounted for 83.6, 83.8, 53.7%. This signifies high water demand from these sectors which, as a result, were major sectoral drivers for water demand. Sun and Yan (2020) calculated the gray water footprint of intermediate and final consumption in 30 provinces and 17 sectors in China from 2002 to 2012, finding that agriculture was the biggest source of gray water footprint while four other industrial sectors, including commerce and transport, showed considerable footprint, yet their aggregate was far below that of agriculture, and that five other industrial sectors, including manufacturing, had remained small in such footprint.

5.2.3 Rising Demand for Water Resources: Changes in Residential Water Footprint

In 2002, Dutch scholar Hoekstra coined the term "water footprint" based on "eco footprint", measuring the direct and indirect impact on water resources from final consumption throughout its entire life cycle, thereby providing a new paradigm for strengthening water management. Since its conception, the research on water footprint has been constantly expanding, and water footprint of residential consumption, in particular, has raised a flurry of chatter across the world, including in China, where the pressure from residential consumption on water resources has been mounting with its rising economy and standard of living. Cai et al. (2019) made a study on the blue water footprint and gray water footprint of urban household consumption in China (the former refers to the surface and underground water consumed in product supply chain; and the latter means the total fresh water needed to dilute pollution to the level of natural background concentration or environmental standard). The study found that water footprint per capita brought by urban household consumption fell from 1992 to 2012, which was mainly attributable to technological progress. The study

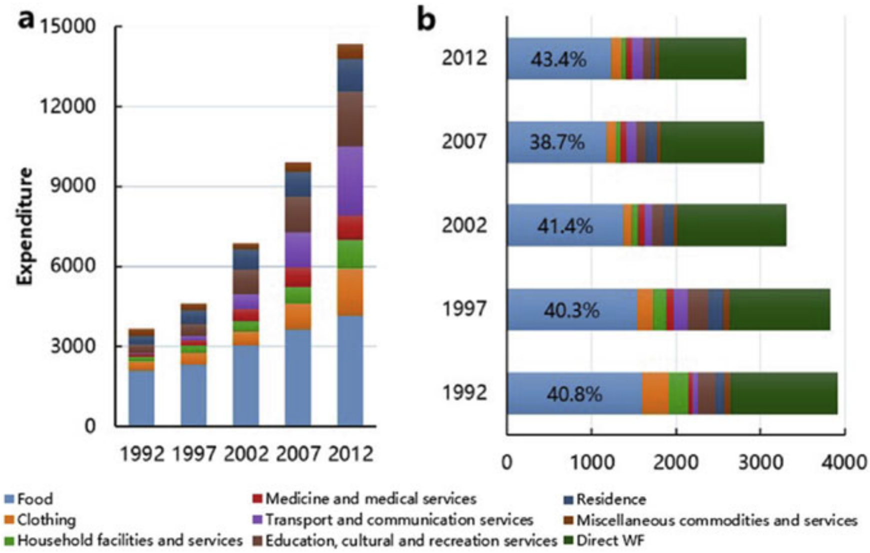


Fig. 5.12 Change in consumer expenditure structure and water footprint for Chinese residents from 1992 to 2012. Source of image: Cai et al. (2019)

also concluded that food consumption was the biggest contributor to total water footprint and such footprint has been on the rise since 2007, which can be explained by the rising meat consumption in the diet thanks to higher income, and meats consume much more water than other foods. Other studies also echoes the importance of food consumption to water footprint. Due to the high intensity of water usage in agriculture and China's top ranking in the water footprint of both food consumption and production, measurement of water footprint in this respect has always been the centerpiece of domestic research (Fig. 5.12).

The dynamic temporal variation in water footprint of food consumotion has attracted growing interest from the research community in recent years. The current consensus from research findings is that water footprint of food consumption is on the rise. Tian et al. (2013) chose major crops and measured water footprint of their consumption in China from 1978 to 2010. The results revealed an increase of 2.01% in water footprint in 2010 from 1978. Yang and Mu (2018) collected the panel data of 31 provinces (municipalities and autonomous regions) from 1999 to 2012 and assessed the changes in food consumption mix and variation in water footprint in the context of higher income with the QUAIDS model, discovering that consumption of various foods showed steady increase with rising income of urban dwellers, and that foods of higher water footprint such as melons and dairy products saw faster increase in consumption, leading to a sustained ramp-up in per capita water footprint of food consumption. From 1999 to 2012, the per capita figure grew by 32.8%, of which faster growth was spotted in northeast and central China. Zheng et al. (2019) measured the water footprint of food consumption of urban and rural residents, concluding that water footprint of agro-products was constantly rising for urban residents but declining for rural dwellers. Total water footprint of agro-product consumption in urban areas rose from 129.8 billion m^3 in 1990 to 378.44 billion m^3 in 2015, and that in rural areas dropped from 362.91 billion m^3 to 272.73 billion m^3 during the same period. In terms of contributors of water footprint, from 1990 to 2015, the size of urban population, urban consumption structure and rural consumption structure were the key drivers for rising water footprint of agro-product consumption, of which the size of urban population stood out most. Consumption other than food, on the other hand, contributed less to water footprint. As was vividly illustrated by Chai et al. (2020) in their study (see Fig. 5.13), food consumption caused the most residential water footprint. Clothing, among other consumption items, also had a major impact; housing, transport, communication, cultural services, education and entertainment were of less visible importance to water demand as less water resources were involved in these commodities and services.

Chai et al. (2020) also pointed out that though water footprint brought by other consumption expenditures were relatively smaller, a continuous rise was observed in recent years. From 2012 to 2018, Chinese resident's water footprint of expenditures other than food consumption surged from 29 m^3 per capita to 45 m^3 per capita, the growth of which had overtaken that of food consumption. This implies that as resident's consumption continues to expand and upgrade, expenditures other than food, such as clothing, housing, transport and communication, cultural services, education and entertainment will play an increasingly significant role in water footprint impact (Fig. 5.14).

The following three factors have stood out in the perception of the contributors to growing water footprint of residential consumption:

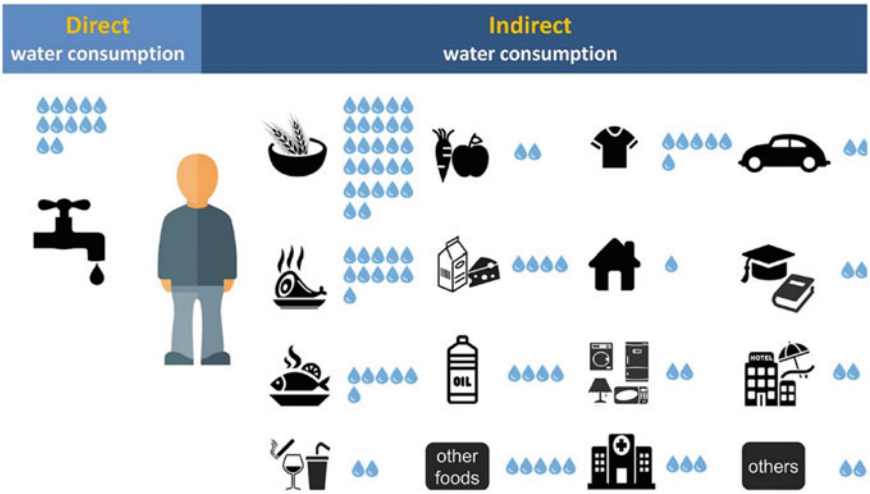


Fig. 5.13 Direct and indirect water footprint of residents and composition of water footprint. Source of image: Chai et al. (2020)

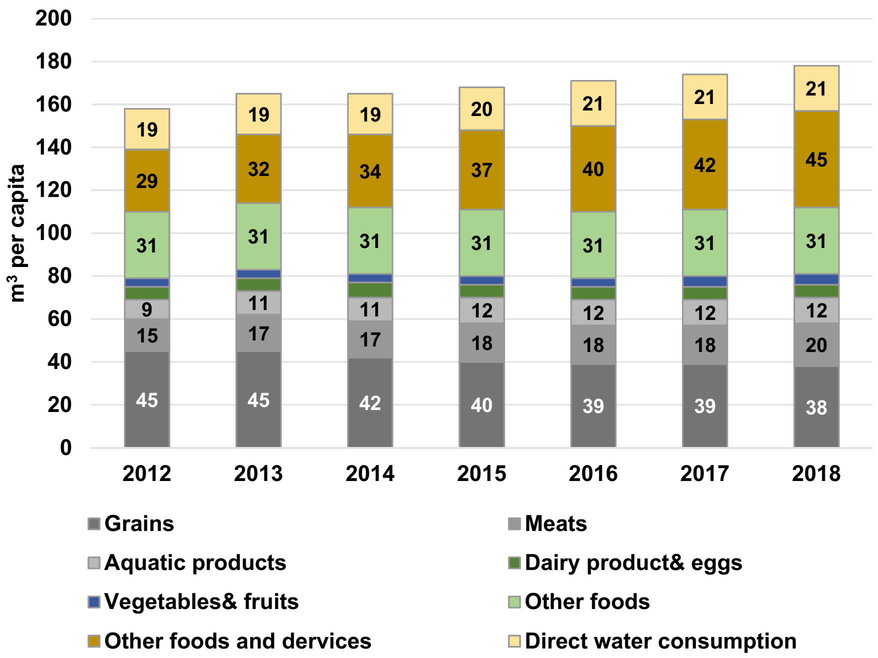


Fig. 5.14 Blue Water Footprint of Chinese Residents from 2012 to 2018. Source of image: Chai et al. (2020)

(1) Income, Yuan and Hu (2011) compared the water footprint of food consumption by different income groups and spotted great disparity in the virtual water content in food consumption in Beijing, with water footprint of food consumption increasing with income. Such disparity resulted from the variation in consumption level and consumption mix among income groups. Xu (2018) analyzed the changes in food consumption and its water footprint characteristics through food consumption system modeling, which indicated that higher income has involved more out-of-home dining and larger proportion of meat and fruit consumption; meanwhile, higher pressure on water resources supply and demand was expected due to changes in food consumption mix.

(2) Lifestyle. A study by Chai et al. (2020) suggested that water footprint of resident's consumption was subject to consumption style, dietary preferences, etc., and it was critical to understand how lifestyle affected water footprint of consumers in order to grasp the consumer demand for water resources. Generally speaking, the priority for an underdeveloped country or region in resources consumption is meeting basic dietary needs, followed by nutritional needs such as increasing the uptake of fat, animal-based foods and fruits; while in developed nations where citizens pursue a more tasteful way of life that stresses the social and cultural elements of food, so the share of beverages such as tea and coffee is

likely to grow, thus pushing up the demand for water resources (Gerbens-Leenes et al. 2002).

(3) Urbanization and industrialization. Both economic boom and population growth during urbanization and industrialization trigger greater demand for water. Higher standards of consumption, massive rural–urban migration, and overall growth in consumer demand, consumption upgrade, increased need for meat and vegetables in food consumption—all these changes will place China's water resources under greater pressure and make water shortage even worse. Meanwhile, China's water resources are further challenged by regional disparity, technical difficulty in resource utilization and in water diversion between river basins, and the supply of crops and other key agro-products is increasingly at odds with the environmental capacity of resources. Hoekstra and Mekonnen (2012) rightly pointed out that the shift from a traditional extensive or mixed agricultural system to an industrial agriculture system was inevitable during industrialization, which would prompt a hike in blue water and gray water footprint per unit of animal product. Li et al. (2017) stated that sprawling urbanization, population growth and expansion of industrial production were major impediments to urban water saving.

Going forward, further economic growth and household consumption will trigger mounting pressure on water demand. In terms of dietary composition, urban demand for higher nutritional value would entail tremendous growth potentials for vegetable and meat consumption, together with the rapid growth of per capita consumption of aquatic products and fruits. As a whole, the dietary mix of future urban residents will shift from plant-based food to a blend of both plant and animal-based products, with growing uptake of the latter. Since animal-based food production generally involves more water use than plant-based food, future demand for food will generate more pressure for the sustainable use of water resources. In addition, a spike in demand for clothing, housing, transport, cultural services, education and entertainment will also ensue, putting greater strain on water resources with expanding consumption. Other than the surge in water demand implied in household consumption, the demand for direct water use has also been on constant increase. According to the statistics published in *China Water Resources Bulletin*, China's household water consumption was up 7.3% from 2010 to 2016, considerably higher than the growth in total water use. With growing urbanization and industrial restructuring, the share of urban household use is expected to rise further, aggravating urban water shortage, and, to some extent, hampering sustainable development in some cities. Given the mounting strain on water consumption, water table drop and inefficient utilization of water in China, it is necessary to draw attention to water pressure from household consumption, especially food consumption, and encourage citizens to change their consumption mix and save water from the demand side. Ample evidences have illustrated the contribution of changed food consumption (eg: more vegetables and less meats) to a healthier lifestyle and reduced pressure on water demand from food production. Potential for water conservation on the demand side is yet to be further unleashed.

5.3 Addressing Changes in Water Resources Demand in Key Industries in the Context of Climate Change: A Case Study of Power Sector

5.3.1 Current Development of Power Industry in China

5.3.1.1 Analysis of Power Supply in China

Power sector in China has enjoyed booming development over the last decades, especially since the turn of the century. As is pointed out in *2018 Annual Development Report on Power Enterprises in China*, the power sector has entered a critical stage of transformation, restructuring and gear shifting. Driving its high quality growth shall underpin the "clean substitution" on the supply side and the "power substitution" on the consumption side of energy (Fig. 5.15).

Overall, electricity generation in China has been climbing steadily in recent years. In 2017, total power production hit 64,951.4 TWh, an annual increase of 6.4%. In contrast, thermal power generation showed lackluster annual growth at 4.9% on average throughout eight years. Despite the dominant position of thermal power in terms of absolute quantity, clean energy has sustained superior growth rate that overtook thermal power by a large margin. The annual growth of wind, hydro and nuclear power averaged at 31.0%, 7.3% and 18.9% respectively, higher than that of total power generation. An overview of the power sector in China shows that the trend of clean substitution is taking shape.

5.3.1.2 Analysis of Power Demand in China

Of the seven sectors on the consumption side (1-agriculture, 2-industry, 3-construction, 4-transport, storage and post, 5-wholesale, retail trade and hotel, restaurants, 6-others and 7-residential consumption), industry has always been the dominant electricity consumer, followed by residential consumption. Agriculture consumes the least electricity (Fig. 5.16).

Figure 5.17 illustrates total power consumption in China from 2010 to 2017 and the absolute growth and annual growth rate by sector. Power consumption from 2010 to 2017 grew by 22,886.5 TWh, averaging at 6.4% on a yearly basis, of which over half of the increase was attributable to the industrial sector. Despite this, the sector only reported annual growth of only 5.5%. Likewise, the consumption growth in agriculture was also below the annual average, standing at 198.6 TWh with a growth of 2.7%. Overall, the power use increase in transportation, wholesale and retail trade and others was lower than that of industry and residential consumption, yet the above three sectors, a major part of the tertiary industry, hit 9.9%, 10.1% and 10.3% in annual growth respectively, taking the top three spots out of seven sectors. What lies underneath is the profound impact of industrial restructuring on power consumption.

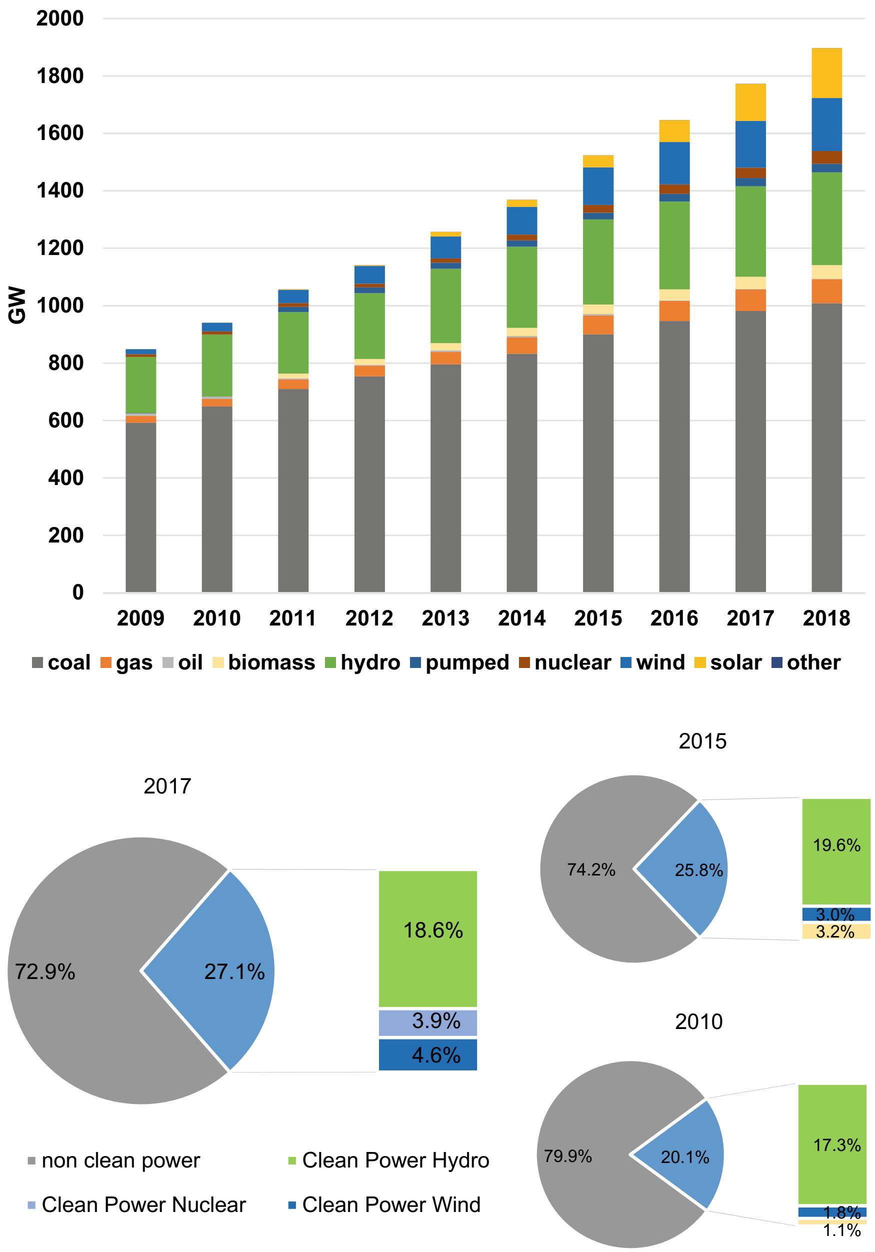


Fig. 5.15 The electricity generation by source in China

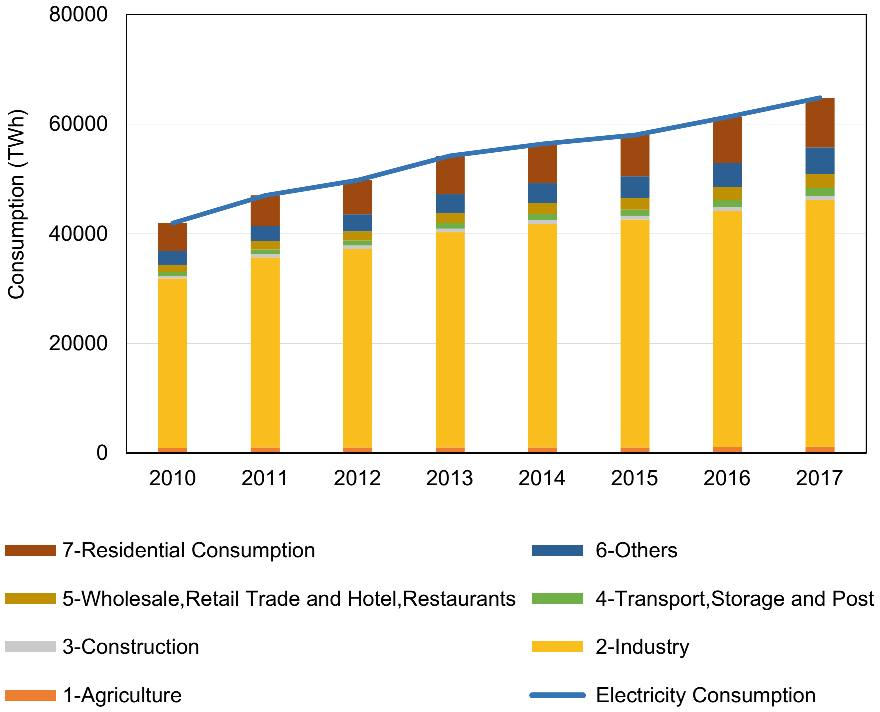


Fig. 5.16 The electricity consumption by sector in China

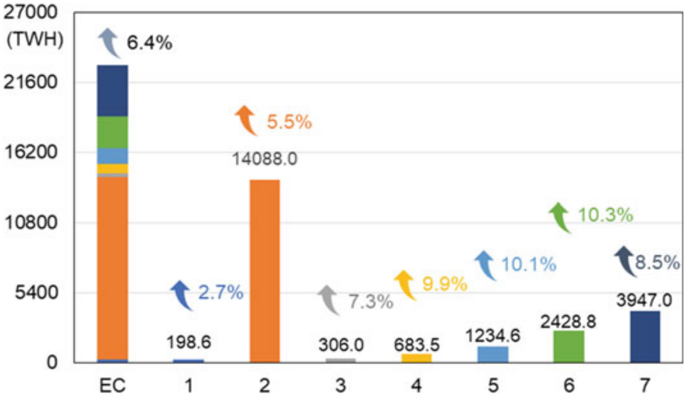


Fig. 5.17 The annual growth rate and added value of electricity consumption (EC) by sector in China, 2010–2017 (the code of consumption sectors consistent with Fig. 5.16)

It shows the promise of the tertiary industry in promoting "power substitution" on the consumption side. It's also worth noting that despite the lower annual growth of residential consumption than the three sectors of service industry, its momentum and speed of growth remained strong and steady, meaning that improvement in people's livelihood has spurred electricity demand, with tremendous potential for emission reduction and energy conservation, which also prompts the pressing need of "power substitution" and "clean substitution" in this field.

5.3.2 Power Industry's Demand for Water Resources

As essential natural resource and strategic economic resource, water underpins economic and social development, and sustains ecological environment. The industrial sectors in China account for 21.0% of China's economic and social water demand (2018 China Resources Bulletin). Summarized from the existing researches, nearly 40.3% of water demand of industrial sectors comes from the power sector in 2015, which is closely associated with the power generation process and the current power supply structure in China, while the demand of iron & steel, textile, and chemical sector only account for 1.90%, 2.50%, and 5%, respectively. In 2018, 70.3% of power generated in China came from thermal power stations (generally including coal-fired, gas-fired, fuel-fired, biomass and waste power production, *2018 CEC Power Generation Statistics Report*), 17.6% from hydropower, 7.8% from wind and solar, and 4.2% from nuclear power (Fig. 5.18). Over 90% of the installed capacity of thermal power generation are coal-fired power units. Of the aforementioned power generation

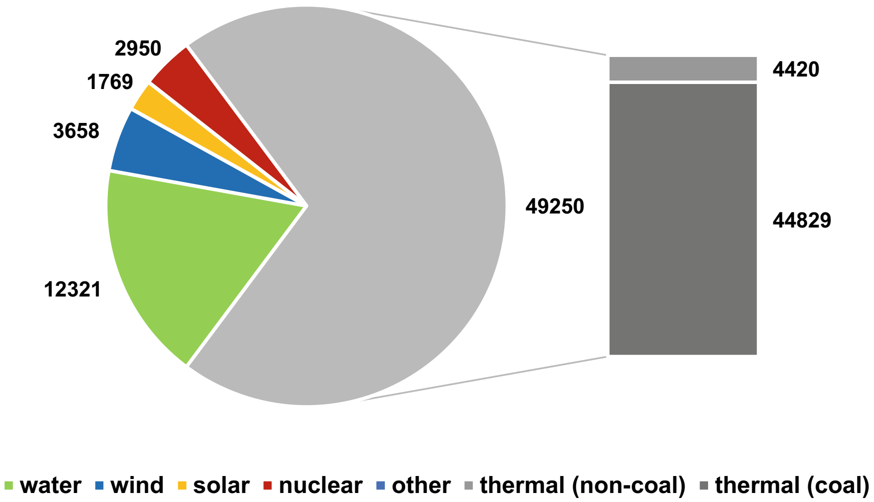


Fig. 5.18 China's power generation supply (TWh) in 2018

technologies, both thermal and nuclear power production depends on water for steam replenishment and cooling, etc. For coal-fired power stations, water is also consumed in auxiliary processes such as desulfurization, dust removal, coal yard, etc. Of these production processes, cooling is the biggest contributor accounting for over 90% of water consumption. To illustrate, based on water withdrawal quota for thermal power, a once-through cooling coal-fired power generator unit with an installed capacity of 600 MW requires approximately 300 million m^3 of water annually, equal to annual household water use for 4 million people.

Thermal power and nuclear power stations both entail enormous amounts of water for operation, yet their impacts on water resources are distinctly different. As of 2019, the installed capacity of nuclear power in China stood at 44.64 GW. Since nuclear power production depends on the gigantic energy released by nuclear reaction of fission fuels, of which the transport is relatively more convenient, all nuclear power units in operation and under construction now in China are located in coastal regions with once-through cooling from seawater, in view of safety and water availability, etc. Over 100 billion m^3 of sea water is consumed annually for this purpose (*2018 China Water Resources Bulletin*, 2018). As fission fuels can be conveniently transported and the nearly infinite seawater cannot be directly put to socio-economic use, no direct water demand is incurred in this respect, thus nuclear power bears no direct impact on the current water resources in China.

In contrast, coal-fired power stations entail large quantities of coal for fuel. Most of coal reserves in China, despite its extensive geographical distribution, are concentrated in the north, relying on powerful means of transportation across regions. Meanwhile, due to the environmental policies for pollution control in developed regions such as eastern and southern China, pithead power plants close to coal mines has become a more economically viable option, giving rise to water shortage in north and northwest China—the arid regions abundant in coal mines but scarce in water. For example, the five provinces (autonomous regions) in northwest and north China, namely Shanxi, Shaanxi, Ningxia, Inner Mongolia and Xinjiang, represent about 76% of total coal reserves in China but a mere 6.14% of the country's water resources. The coal-fired power plants built adjacent to coal mines have worsened water shortage.

The distribution of installed capacity of coal-fired power plants and their water consuming technologies also exert impact on local water resources. According to the survey on cooling types of China's coal-fired power units in this study, by 2015, the installed capacity of coal-fired power plants in northern China made up over half of those in the country, and circular cooling was adopted in over half of these power units in the region. Water demand of circular cooling is over 95% lower than that of once-through cooling at the same installed capacity, and most new units adopted air cooling technique of higher water efficiency. However, advanced cooling technologies are mainly installed in some regions lacking water such as northwest and north China, for which still face considerable pressure for water even in the context of technological progress. Besides, technology progress may further cause the energy rebound effects, and then trigger the increasing effect on water consumption in the power sector. Not only that, the stress is mutual: water shortage resulted from power plants has become the stumbling block of their own operation.

Generally speaking, nearly half of the industrial water demand in China stems from the power sector, most of which are coal-fired power plants; water use technologies adopted in coal-fired power plants exert defining impact on total water demand, but most of the coal-fired power plants installing advanced cooling technologies are located in water shortage regions that have limited water-saving potential; while due to the circular cooling will reduce the generating efficiency, the once-through cooling might still be the preferred choice of coal-fired power plants in regions with an abundance of water. Therefore, water demand of the power sector will probably be the largest industrial water consumer, and there still have great necessity to discuss the water demand issues in power sector, such as the construction of coal-fired power plants is subject to further justification and assessment; coal-fired power plants have triggered acute water shortage in some regions, which are scarce in water in the first place. To be summarized, coal-fired power development in the future, while meeting the need of power production, should accommodate water availability and other environmental factors with sound planning of its footprint.

5.3.3 Trend of China's Power Industry in Future: Methods, Tools and Conclusions

5.3.3.1 Method Overview

A crucial energy sector in socioeconomic activities, the power sector is subject to a variety of interconnected factors in its development. The change in one factor would incur a string of changes in the others, which adds to the challenge of forecasting development of the sector, and calls for mathematical modeling for trend analysis.

In terms of modeling methodology, the methodological tools in the power sector mainly fall into two categories: bottom-up and top-down, different from each other in the angle of research. With its roots in traditional economic model, the top-down approach employs a macro socio-economic perspective and seeks to describe the changes in supply and demand of the energy system as a result of macroeconomic shifts, considering the impact of economic changes on varied sectors and price elasticity as the main economic index, but is unable to delineate the impact from technological trends. Currently, top-down models used in diagnosing power industry and other energy sectors mainly include macro-econometric model, general equilibrium model (CGE) and input–output model. On the contrary, bottom-up models aim to diagnose the comprehensive effect produced by technological changes and their impact on the energy-environmental-economic system based on detailed technical description of varied techniques and processes. The bottom-up energy system models boast abundant description of energy technologies and are based on technical processes adopted by human activities that reflect energy consumption and production, and provide forecast on energy consumption and way of production. Study on the development trend of the power industry should be conducted by employing the suitable modeling methods for the specific topic of research.

This study centers on the impact of China's power sector development on water resources, assuming that it meets the needs of future power consumption. Discussions on the features of power industry in previous sections inform us that the demand for water resources shows strong correlation with the technology adopted and the spatial variation of water resources. Therefore, a bottom-up model based on technological difference is more relevant for this analysis. MESEIC (Multi-regional model for Energy Supply System and their Environmental Impacts), an optimization model of the power sector based on technological difference, is adopted for the assessment on the trend of China's electricity industry. Since such development involves geographical uncertainties, different development scenarios and CO_2 emission targets can be hypothetically set for discussion.

5.3.3.2 Modelling

MESEIC model is a multi-regional, bottom-up optimization model for the power sector. In light of the great variation in power demand and resources endowment among regions, and provincial differences in technological features and grid transmission due to the provincial-based management of the sector, this model divides Chinese mainland into 32 provincial zones (of which Inner Mongolia is broken down as East Inner Mongolia and West Inner Mongolia) based on the actual administrative demarcation. Cross-regional power transmission is also considered for an optimized simulation of power supply and demand in provincial zones from 2015 to 2050. 14 mainstream power production technologies are included in the model, including various fossil fuels such as coal-fired and gas-fired power generation technologies, renewables such as wind, solar, hydro and biomass power, as well as nuclear power.

Based on the scenario framework of SSP (Shared Socioeconomic Pathways) that shows varied development scenarios stemming from varied socioeconomic development paths, three scenario assumptions are chosen, namely sustainable development scenario with low power demand (SSP1), regular development scenario (SSP2) and high challenge scenario with growing power demand (SSP5); meanwhile, as over half of the CO_2 emissions from human activities are attributable to the power industry, the impact of varied CO_2 emission targets has been factored in when setting the scenarios. Specifically, both the emission target of no emission restraint and 2 °C emission pathway are considered.

5.3.3.3 Future Trend of Power Industry Development

When meeting the 2 °C target (Fig. 5.19 a-1, b-1, c-1) in 2050, China's total coal power will be substantially lower than in regular scenario (Fig. 5.20 a-2, b-2, c-2), which testifies to synergistic benefit of reduced coal power to the fulfillment of CO_2 emission target. Meanwhile, without factoring in CO_2 emission target, varied power demand

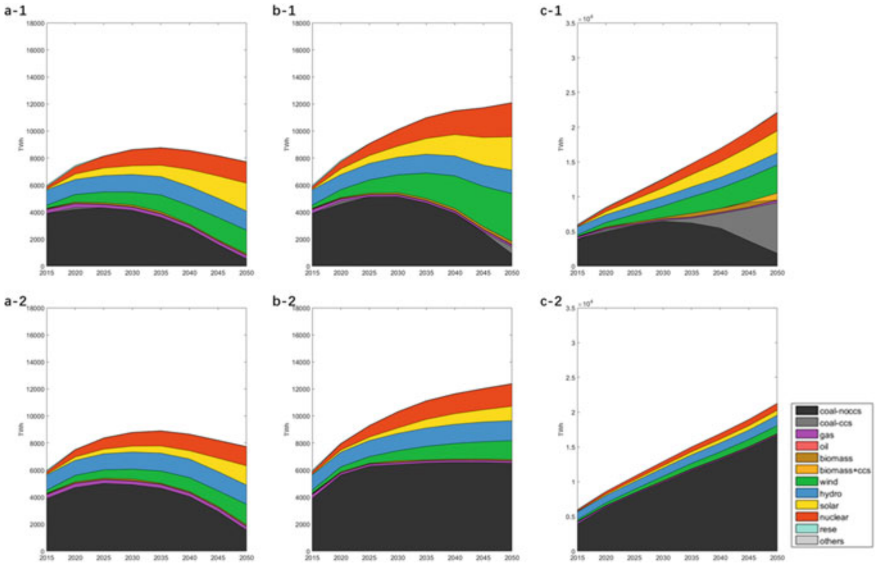


Fig. 5.19 The generation of China's power plants under different scenarios (SSP1, SSP2 and SSP5) and CO_2 emission reduction targets (REF: Regular scenarios and 2 °C targets;) during 2015–2050. (a-1) SSP1 with 2 °C; (a-2) SSP1 with REF target; (b-1) SSP2 with 2 °C target; (b-2) SSP2 with REF target; (c-1) SSP5 with 2 °C target; (c-2) SSP5 with REF target

will remain a key factor in power development, especially coal power. Growth in power demand bears significant impact on coal power generation. However, under the 2 °C target and in sustainable development scenario (SSP1) and regular development scenario (SSP2), coal-fired power generation comes under minor influence from increased power demand, hovering at a low level; while in high challenge scenario with growing power demand (SSP5), increased coal power is inevitable.

Overall, climate goals produce notable synergistic benefits for reducing total amounts of coal power; yet the surging power demand would inevitably push up coal power generation. Therefore, harsher policy stance is needed to curb the increase of coal power.

5.3.4 Water Resources Risk in Future Development of China's Power Industry and Its Temporal and Geographical Distribution

In Sect. 5.3.3, China's power supply mix in the future under varied scenarios and CO_2 emission targets is estimated through simulation with the optimization model. To assess water resources risk in future of China's power sector, such risk is analyzed on a catchment scale based on the water demand of coal-fired power plants.

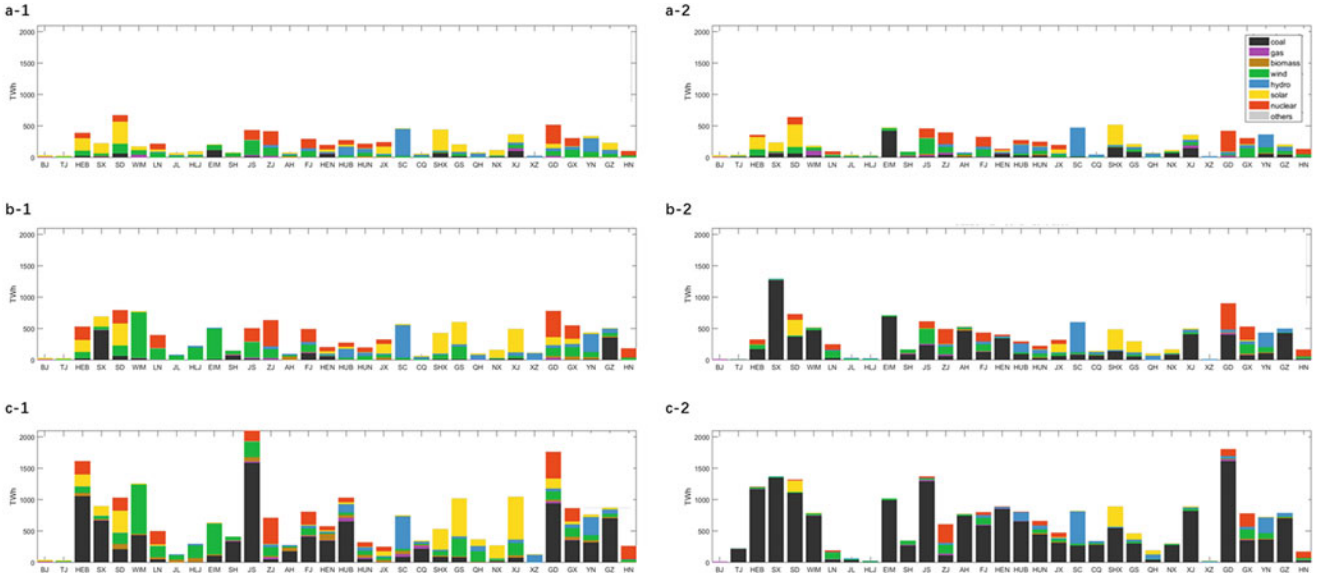


Fig. 5.20 The provincial generation of China's power plants under different scenarios (SSP1, SSP2 and SSP5) and CO_2 emission reduction targets (2 °C: Regular scenarios and REF targets;) during 2015–2050. (a-1) SSP1 with 2 °C; (a-2) SSP1 with REF target; (b-1) SSP2 with 2 °C target; (b-2) SSP2 with REF target; (c-1) SSP5 with 2 °C target; (c-2) SSP5 with REF target

5.3.4.1 Data Basis and Methodology

Assessment of water resources risk from the future development of the power sector requires data of water demand of coal-fired power plants and regional distribution of water resources. This study has built a database of over 98% of the installed capacity of coal-fired power plants currently in operation in China, which consists of geographical location, operation status, technical parameters, water withdrawal data, etc. In addition, information of power units under planning or awaiting construction has also been collected for the sake of new coal power plants in the future. The total installed capacity of coal-fired power plants in the database has exceeded 1960 GW, over twice the size in 2015, which could be used for mapping out the potential distribution of such plants in future. As complementary information, data of gas-fired power plants is also embedded in the database. All these data, coupled with the provincial power demand calculated with MESEIC model elaborated in Sect. 3.2, the geographical distribution of future water demand from coal-fired power generation can be obtained. It should be noted, however, air cooling is adopted for all new power units in northwest China.

Data from Aqueduct Water Risk Atlas developed by World Resources Institute is used in the forecast of water resources. The data consists of estimated water resources of different catchments under varied climate scenarios (Representative Concentration Pathways, RCP). The available water resources (Ba) in the database refers to the total amount of water in a catchment before withdrawal, calculated by runoff from upstream minus water consumed upstream plus runoff within the catchment, where the historical annual runoff is the annual average from 1950 to 2010. A simulated forcast of future water resources under the four climate models is conducted on this basis.

In this study, Water Stress Index (WSI) is adopted to measure the impact of water withdrawn by the power industry on the local water resources in a given region. Water stress is expressed as the ration between water withdrawn from a certain region and the available water resources there. Meanwhile, given the uncertainty of geographical location of future power plants, Monte Carlo simulation is adopted to obtain the probability distribution of coal-fired power plants in a given region and to grasp its water stress risk.

5.3.4.2 Analysis on Water Resources Risk in Future Development of China's Power Sector

(1) Water Stress Impact from Changed Cooling Method in Current Coal-Fired Power Units

Coal-fired power units in northern China as described in Sect. 3.2.3 still boast potential to reduce water demand by renovating the cooling technique. Changes resulting from renovating air cooling system in the existing coal-fired power plants in northern China are illustrated. In 2015, considerable water stress was produced in some regions in north and northwest China despite the replacement of circular cooling units with air cooling system. Therefore, the construction of coal-fired power plants in these regions would aggravate water resources risk, as water stress cannot be fully alleviated by air cooling units.

(2) Analysis on Water Resources Risk in Future Development of China's Power Sector
Water stress criterion says when the water stress index in a certain area reaches 0.05 or above, such area is subject to notable water stress. Given the sole focus of this study on the power sector, 0.05 is determined as the threshold for water stress of a specific area. Figure 3.7 illustrates the cumulative probability distribution of water stress of 0.05 or above stemming from coal power plants in varied scenarios—sustainable development scenario (SSP1), regular development scenario (SSP2) and high challenge scenario (SSP3) and under different climate targets.

In regular scenario, water stress risk from coal-fired power plants by 2050 will be concentrated in northwest China and north China catchments. Compared to sustainable development scenario (SSP1), in regular scenario (SSP2) and high challenge scenario (SSP5), the total number of coal-fired power plants will stabilize or increase with growing power demand, so the water stress risk in northwest and north China will not be mitigated; while under the 2 °C target, the power sector in China could manage to ease water stress risk (index = 0.05) in various catchments in China when meeting future power demand. However, such risk will not be eradicated and the coal-fired power aggregate still needs to be capped.

5.4 Policy Recommendations for Confronting Water Resources Challenge in China

China is and will be plagued by water shortage for a long time to come. Moreover, agriculture is and will far outstrip industry in making the biggest contribution of over 60% to water consumption. In contrast with the stable water use in agriculture and industry, household and environmental consumption has been on constant rise. In the meantime, changes in people's dietary structure and way of life have given rise to their indirect water footprint. In this context, continuous upgrade of water efficiency in agriculture and reduction of water footprint in household consumption hold the key to easing water stress.

In industrial sectors, besides improvement in water efficiency of water consuming processes in industrial production, a system-wide optimization of industrial water use is also essential. The power sector, especially coal-fired power plants that are mainly built in the arid regions abundant in coal mines but scarce in water, faces more serious water resource challenges caused by the uneven distribution of water resources. What's more, it is expected that the demand for electricity has great potential to increase along with economic growth and urbanization, and this further force the power sector to face a serious water resource challenge. Therefore, the share and geographical distribution of coal-fired power generation in the entire power system should be adjusted. Northwest China is home to massive coal-fired power basis, and water stress would still exceed the warning threshold in some parts of the region even if air-cooling is adopted in all the units. Therefore, the potential constraint of water resources on the development of coal power in different regions must be considered, in particular in northwest China. Meanwhile, notable synergistic benefit exists between emission target to combat climate change and the reduction of water demand from coal power, which provides grounds for proactive emission reduction efforts under the climate policy framework.

More rigorous resources management should be adopted. A period of intensified efforts in pollution control has put to a stop the worsening water environment in China. Nevertheless, the current water management system is not yet full-fledged due to the legacy of duplicated and fragmented government functions in water management, among other problems. Confronting the challenge requires a strengthening of water management system for most efficient utilization, conservation and sustainable use of water resources in a holistic manner. Possible options include creating a coordination mechanism for water management and implementing water right trading system, etc.

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Chapter 6
The Impacts of Electric Vehicles on Resources and Supply Chains Sustainability

Han Hao and Xin Sun

Abstract The fast development of electric vehicle market globally leads to highly dynamic critical metal demands, which brings potential resource and supply chain sustainability challenges. In this chapter, we project future lithium, nickel, cobalt and manganese demands driven by global electric vehicle deployment under different battery technology scenarios, and investigate the impacts on resource and supply chain sustainability. The results suggest that future critical metal demands are substantially affected by battery technology roadmap. Considerable risks exist in the supply chains of battery materials. Policy recommendations are proposed to cope with the upcoming challenges.

Keywords Electric vehicle · Supply chain · Critical metal

6.1 Background

6.1.1 An Overview of Electric Vehicle Development

In the context of global efforts in addressing climate change, energy security and environmental pollution, electric vehicles (EV), as a new means of clean transportation, have enjoyed booming development (EV in this article includes BEV, Battery Electric Vehicles, PHEV, Plug-in Hybrid Electric Vehicles and FCV, Fuel Cell Vehicles) with surging global sales over the past decade, hitting 2.2 million in 2019, a penetration of 2.5%. By market share, Norway tops the world with EVs accounting for 40% of all vehicles (IEA, Global EV Outlook 2019); and China is the world's largest EV market which represents over half of the world's EV sales in recent years, as is illustrated in Fig. 6.1. The sales of EV in China soared from 17,500 in 2013 to

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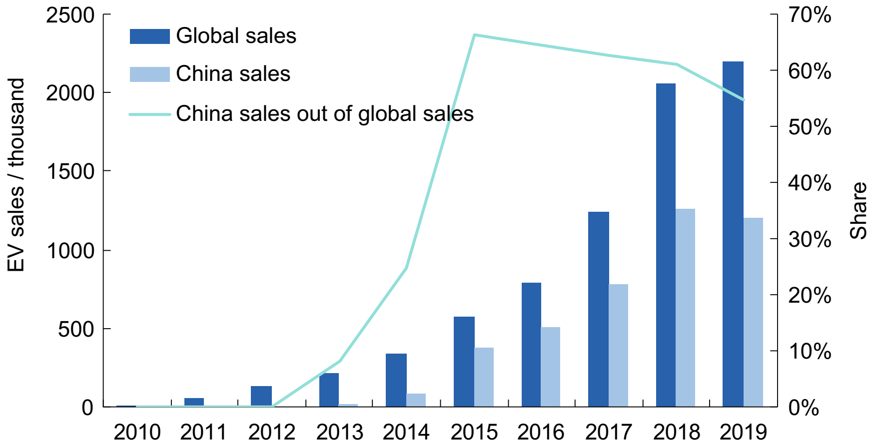

Fig. 6.1 Sales growth of EV in the world and in China

1.2 million in 2019, with a rise in market share from 0.1 to 4.7% (CAAM, Current status of China's automotive industry 2020).

A great many favorable technological and policy factors exist for the sustained development of EV.

First, from a technological standpoint, the thriving innovation in battery technologies has rapidly brought down the cost, which is approaching the critical point of $100/kWh, indicating that the full life cycle cost of EV will soon be as competitive as conventional vehicles.

Second, from a market perspective, mainstream carmakers such as Volkswagen and Toyota have embarked on a transition towards EV while emerging EV manufacturers such as Tesla and BYD have thrived. The e-mobility strategies of these OEMs have prompted upstream and downstream businesses to move towards electrification, which represents the strategic future of the entire auto industry and its industrial chain.

Third, from a policy viewpoint, countries and regions such as China and California in the US have spearheaded the EV credit system, which is set to become the main policy driver for EV market expansion in the context of EV purchase subsidy phase-out across the world. Meanwhile, timetables for the ban on gasoline vehicles in some countries could also facilitate the rapid scale-up of EVs.

Driven by the aforementioned factors, EV is on track to maintain its robust growth. According to Electric Vehicles Initiative (EVI), the global penetration of EVs is projected to reach 30% by 2030 (IEA, Electric vehicles initiative 2020). In China's recently announced strategy of industry development, an ambitious target for the market penetration of EV is set at 25% by 2025 (MIIT, Planning of new energy vehicle industry 2021).

6.1.2 An Overview of Battery

Battery is at the core of EV components, and its installation has soared driven by the flourishing EV market, jumping from 3.7 GWh in 2014 to 62.2 GWh (CABIIC, China automotive battery statistics 2020) in 2019, implying a higher growth rate than EV sales.

Currently, EV batteries are mainly based on Li-ion chemistry, which consists of multiple chemical forms commonly differentiated by cathode materials of batteries, including NMC, NCA, LFP, LMO, etc. Batteries vary in cost, energy density, safety, service life, material demand, etc., as illustrated in Fig. 6.2. NMC is mainly used in passenger vehicles with a high requirement for energy density; while LFP is more suitable for large vehicles. Regarding the key resources mentioned in this chapter,

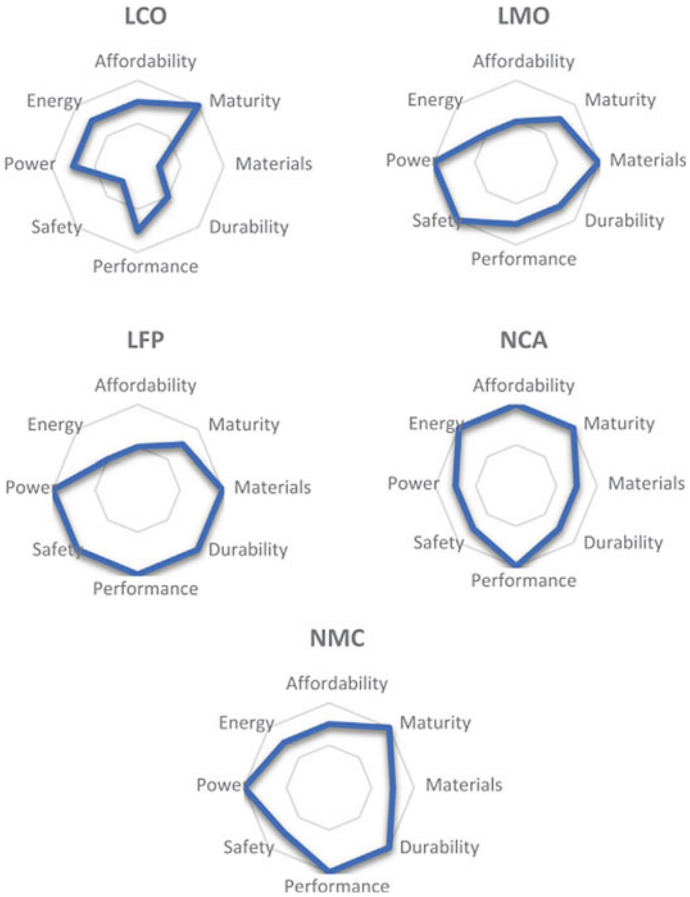

Fig. 6.2 A comparison of technical performance of mainstream batteries (Zubi et al. 2018) (directly cited from source literature)

NMC requires lithium, nickel and cobalt; while LFP and LMO only rely on lithium and demand less for critical resources.

Currently, rapid development of battery technologies has spawned tremendous technological innovation of mainstream Li-ion batteries, such as the blade battery of BYD, CTP (Cell-to-Pack) technology of CATL, etc. Swift improvement of key indicators such as cost and energy density has made EVs a considerable rival of conventional vehicles. Meanwhile, the steady development of next generation battery technologies such as solid state, Li-S, and metal air promises great potential of slashing the cost and improving energy density and other critical resources of battery. However, it should be noted that these technologies are still under experiments with much uncertainty in terms of their technical prospect, thus requiring enormous R&D and industrial input for their sophistication and application.

6.1.3 Overview of Critical Resources

6.1.3.1 Resources Supply

Figure 6.3 illustrated the historical mine production of four critical metals (lithium, nickel, cobalt and manganese). Their respective supplies are elaborated as follows.

Currently, there are two sources which lithium comes from: brine and ore. Though research has proven that extraction from clay or sea water is also theoretically feasible, these are not yet applied in massive production due to high costs as a result of technological immaturity (Sverdrup 2016). The consumption of lithium is on constant rise in recent years on account of the rapid development of EVs, and consequently,

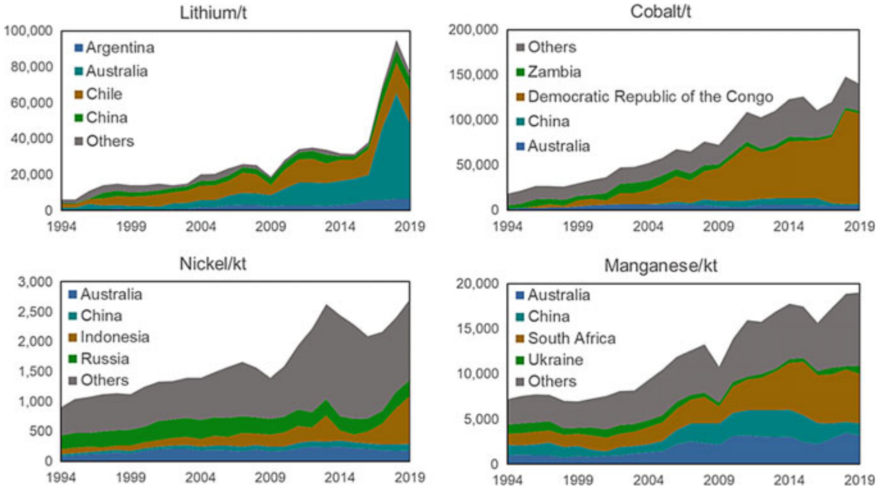

Fig. 6.3 Historical mine production of four critical metal resources

the exploration of lithium ores has been active. By 2019, the identified economically recoverable reserves of lithium was 17 million tons, most of which was in Chile (8.6 million tons), Australia (2.8 million tons), Argentina (1.7 million tons) and China (1 million tons). The identified resources of lithium were approximately 80 million tons, mostly in the "Lithium Triangle" in South America, i.e. Bolivia (21 million tons), Argentina (17 million tons) and Chile (9 million tons) (Mineral commodity summaries 2020).

In terms of primary supply, the global lithium mine production reached 77,000 tons in 2019, of which the main producers were Australia (42,000 tons), Chile (18,000 tons), China (7,000 tons) and Argentina (6,000 tons) (Mineral commodity summaries 2020). For secondary supply, the recycling of lithium currently remains at a low level. Despite the rising awareness of recycling-related laws and policies in multiple countries and regions, the recovery of spent lithium battery is far from being satisfactory (Sun et al. 2018). In 2018, the world recovered approximately 97,000 tons of lithium battery, of which 67,000 tons were from China. At the average energy density of 150 Wh/kg, the total recovery amounted to 15 GWh (Melin 2019). Meanwhile, the world produced about 160 GWh of lithium battery in 2018, and about 30 GWh was discarded correspondingly (Melin 2019), indicating enormous potential for lithium battery recovery.

The cobalt reserves in 2019 was 7 million tons, most of which were in Democratic Republic of the Congo (DRC, 3.6 million tons) and Australia (1.2 million tons), with the former becoming one of the major cobalt producers starting from 1999, and its share in global cobalt production steadily on the rise, supplying around 70% of the world's cobalt in 2019 (Mineral commodity summaries 2020). However, the cobalt supply from DRC is troubled by very unstable policies due to war and political issues, prompting major cobalt companies to invest in cobalt exploration in other countries. Cobalt is a typical companion mineral, of which 90% is mined as a by-product of copper or nickel except for the primary ores in Morocco and artisanal mining in DRC (Fu et al. 2020), which means that the output and price of cobalt does not only depend on its own market but is also prone to the impact of copper and nickel market. In terms of secondary supply, the recovery of cobalt stood low at approximately 10% in 2015 (Sun et al. 2019).

The mining supply of nickel shows a more scattered pattern. In 2019, the global nickel reserves were 89 million tons, of which Indonesia (21 million tons), Australia (20 million tons), Brazil (11 million tons), Russia (6.9 million tons), Cuba (5.5 million tons) and the Philippines (4.8 million tons) ranked among the top. In 2019, the global nickel mine production was 2.7 million tons, with main producers being Indonesia (800,000 tons), the Philippines (420,000 tons), Russia (270,000 tons), New Caledonia (220,000 tons), Canada (180,000 tons) and Australia (180,000 tons) (Mineral commodity summaries 2020). The static reserve and production (RP) ratio of nickel is merely 33 years, lower than that of lithium and cobalt, but RP ratio of nickel mines remained unchanged at around 30 years over the past two decades, meaning that the economically recoverable reserves of nickel vary in close correlation with its output, and no shortage within short or mid-term is predicted as things stand.

The recovery of nickel is relatively high as it is already a mature market. In 2019, secondary production accounted for 47% of the global total nickel supply (Mineral commodity summaries 2020). A notable event in this regard is the resumption of ban on direct transport of nickel ores by the Indonesian government starting January 2020, two years earlier than previously announced, in order to retain raw ores for domestic processing industry and shore up domestic refining and manufacturing industries. This policy might exert considerable impact on the supply and demand of the resource, as Indonesia is the world's biggest supplier of nickel ore.

The supply of manganese is similar with nickel with relatively dispersed reserves and production. In 2019, the global manganese reserves totaled 810 million tons, mostly in South Africa (260 million tons), Brazil (140 million tons), Ukraine (140 million tons) and Australia (100 million tons). In the same year, the world produced 19 million tons of manganese, mostly from South Africa (5.5 million tons), Australia (3.2 million tons), Gabon (2.4 million tons), Ghana (1.4 million tons), China (1.3 million tons), Brazil (1.2 million tons) and India (1 million tons). The static RP ratio of manganese is approximately 40 years, which, like nickel, remains stable over a long period of time (Mineral commodity summaries 2020).

Compared to lithium, cobalt and nickel, the market stays in smooth water for manganese with rare fluctuations in output and prices. The biggest potential risk, however, comes from the very fragile recovery system as there is by far no processing facility dedicated to manganese recycling. Currently, manganese is only recovered as an appendage of steel and reused in the steel industry with discarded and recycled steel. With little flexibility of the recycling system, the high recovery rate in the steelmaking industry tends to fall short of possible surge in demand in other areas of consumption (Sun et al. 2020).

6.1.3.2 Resources Consumption

The final consumption structure of four critical metal resources are illustrated in Fig. 6.4. Details are as follows.

The global final consumption mix of lithium in 2019 is as follows: battery: 65%; ceramics and glass: 18%; lithium-based lubricating grease: 5%; polymer production: 3%; continuous casting mold flux powders: 3%; air treatment: 1%; others: 5% (Mineral commodity summaries 2020). In recent years, the lithium consumption in battery has soared, as consumer electronics, electric tools, EVs and power grid has increasingly adopted lithium battery for energy storage, a stark contrast to the year 2015 when lithium consumed in battery only made up about 30% of its total consumption (Sun et al. 2017).

The battery industry features a growing share in global cobalt consumption each year. In 2018, battery industry comprised 60% of the global use of cobalt, followed by superalloy (15%). Breakdown by country, China is the biggest consumer of cobalt where over 80% is used in battery.

In final consumption, nickel is principally used in stainless steel (69%), alloy (17%) and electroplating (6%) industries. Battery, at only 3% (Nickel institute, about

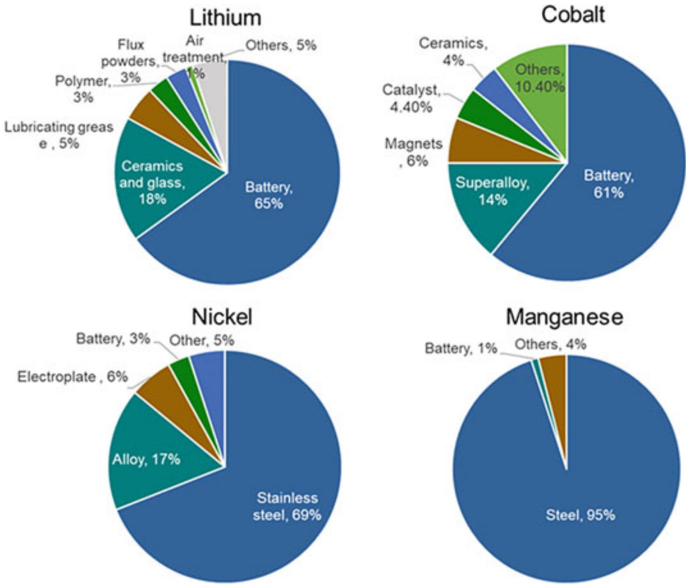

Fig. 6.4 Final consumption of critical metal resources in 2019

nickel 2019), bears very limited impact on the nickel market at present. However, with mediocre annual growth between 10% and 20% for stainless steel and alloy industries and over 30% for battery industry, nickel consumption would be subject to much greater influence from the battery industry as nickel-rich NMC battery gains more popularity.

Manganese consumption is highly concentrated as 95% of it is used in steelmaking and less than 2% in battery. The size of the steel industry is approaching its ceiling in recent years without notable changes The quantitative impact of battery industry on manganese market will remain trivial for a considerable period.

6.1.4 Identification of Challenges

Undoubtedly, the rapid development of EVs will trigger a spike in demand for battery, which will in turn drive up demand for critical metal resources such as lithium, nickel, cobalt and manganese. The size of demand, however, will depend on EV market growth, battery technology development, resources utilization efficiency, etc., with multiple scenarios that require scientific assessment with bottom-up modeling.

Rising demand for critical metal resources will bring two critical challenges. First, sustainability. From a supply and demand perspective, the resources endowment of lithium, nickel and cobalt is less than abundant and it remains a question mark whether the limited resources can support the long-term development of EVs. Will drastic price fluctuations of the industrial chain occured due to resources shortage? To what extent will such shortage be eased by circular economy and other policy measures? Clear answers are needed for these questions.

Second, supply risk. The geographical distribution of natural resources such as lithium, nickel and cobalt is relatively concentrated, meaning that countries and regions with inadequate resources may still be heavily dependent on import despite the adequate global supply in supporting EV development. And this would imply potential risks of supply interruption stemming from economic, political or military issues of the exporting country, jeopardizing the industrial chain of the importer.

Given the above considerations, this chapter will provide a scientific assessment of the sustainability and supply risk based on the projection of EV-associated demand for critical metal resources.

6.2 Demand Projection and Sustainability Assessment of Critical Metals

6.2.1 Projection Method and Basic Assumptions

Demand for critical metal resources driven by EV development hinges on multiple technological, market and policy factors, calling for a simulation through bottom-up modeling with elaborated technical details. For this purpose, the research taskforce built a bottom-up technological model of global light-duty vehicle fleets, in which detailed technical data of vehicle electrification and battery technological development are embedded to simulate the resources demand associated with EV development on a large time scale (2000–2100) and geographical span (140 countries). The model is elaborated in (Hao et al. 2019a, b).

Core basic assumptions in this study comprise vehicle sales, ownership and retirement, EV market penetration, EV electric range, battery technological development, recycling rate of battery materials, etc., which produce the largest impact on the future demand for critical metals. Based on modeling simulation and expert predictions, specific assumptions are applied in the above parameters as in Table 6.1.

Table 6.1 Assumptions of key indicators

Indicators	Assumptions
Sales, ownership and retirement of vehicles	Vehicle sales: global sales of ligh-duty vehicles shall reach 141 million, 187 million and 213 million respectively by 2030, 2050 and 2100; Retirement: global retirement of light-duty vehicles shall reach 84 million, 143 million and 210 million respectively by 2030, 2050 and 2100; Ownership: global ownership of light-duty vehicles shall reach 1847 million, 2883 million and 3659 million respectively by 2030, 2050 and 2100

(continued)

Table 6.1 (continued)

Indicators	Assumptions
Market penetration of EV	For China, US, EU, Japan where EVs experience rapid growth: assuming full electrification becomes a reality in 2070 (the ratio of BEV and PHEV is 3:1), BEV market penetration reaches 100% by 2090, and no significant fuel cell installation in light-duty vehicles; For countries and regions where EVs show slow development: supposing another 10 years is needed for EV market penetration to reach the same level as the above countries
Electric range of EV	Electric range of BEV stays at 300 km; Electric range of PHEV stays at 60 km
Technological development of battery	Build three scenarios for battery technology development: maintaining existing technology portfolio (S1, benchmark scenario), dominance of LFP technology (S2) and dominance of NCA technology (S3)
Recycling rate of cell materials	The recycling rate of various resources from battery reaches a high level by 2030: 80% for lithium and 90% for nickel, cobalt and manganese

6.2.2 Demand Projection for Critical Metals

Figure 6.5 illustrates the demand for critical metals from 2000 to 2100 in the three scenarios of battery technology development. On the whole, the growth in the demand for critical metals varies dramatically among the three scenarios, pointing to the fundamental impact of battery technology on the future demand for critical metals.

Figure 6.5a depicts the demand for critical metal resources in the scenario of keeping existing technology portfolio (S1, benchmark). It is observed that gross demand for lithium, nickel, cobalt and manganese surges, hitting 1.31 mt, 4.33 mt, 1.00 mt and 2.44 mt respectively by 2100; but net demand will see a turning point and fall prior to 2100 due to metal recycling. Despite this, recycling won't reverse the trend in the short run, and net demand for the four metals will maintain steady growth for a long time to come to reach 0.45 mt, 1.13 mt, 0.26 mt and 0.64 mt respectively by 2100, the global primary mining exploitation to meet the net demand in 2100 shall be 589%, 55%, 219% and 5% of that in 2018 respectively.

Figure 6.5b illustrates the demand for critical metal resources in the scenario of LFP dominance (S2), whose most distinctive trait is the considerably less demand for nickel, cobalt and manganese compared to the benchmark scenario. Specifically, the three metals amount to 1.27, 0.29 and 0.72 mt in gross demand in 2100 and 0.33, 0.08 and 0.19 mt in net demand, a drop of about 70% compared to benchmark. This is largely because lithium is the only material needed for LFP as the dominant technology that is free from nickel, cobalt and manganese, hence the drastic decline in their demand. It can be deemed that this scenario is more resource-sustainable compared to the others. In this case, the global primary mining exploitation to meet the net demand for lithium, nickel, cobalt and manganese shall be 572%, 16%, 64% and 1% of that in 2018 respectively.

Figure 6.5c shows the demand for critical metal resources in the NCA dominance scenario (S3), which is notably characterized by a much higher demand for nickel than in other scenarios, registering at 7.04 mt in gross demand and 1.84 mt in net demand by 2100, 63% higher than the benchmark. Meanwhile, the demand for cobalt is also greater than benchmark, reaching 1.37 mt in gross demand and 0.36 mt in net demand by 2100, 37% greater than the benchmark. The main reason is that nickel and cobalt are essential for the cathode of NCA battery, especially nickel which makes

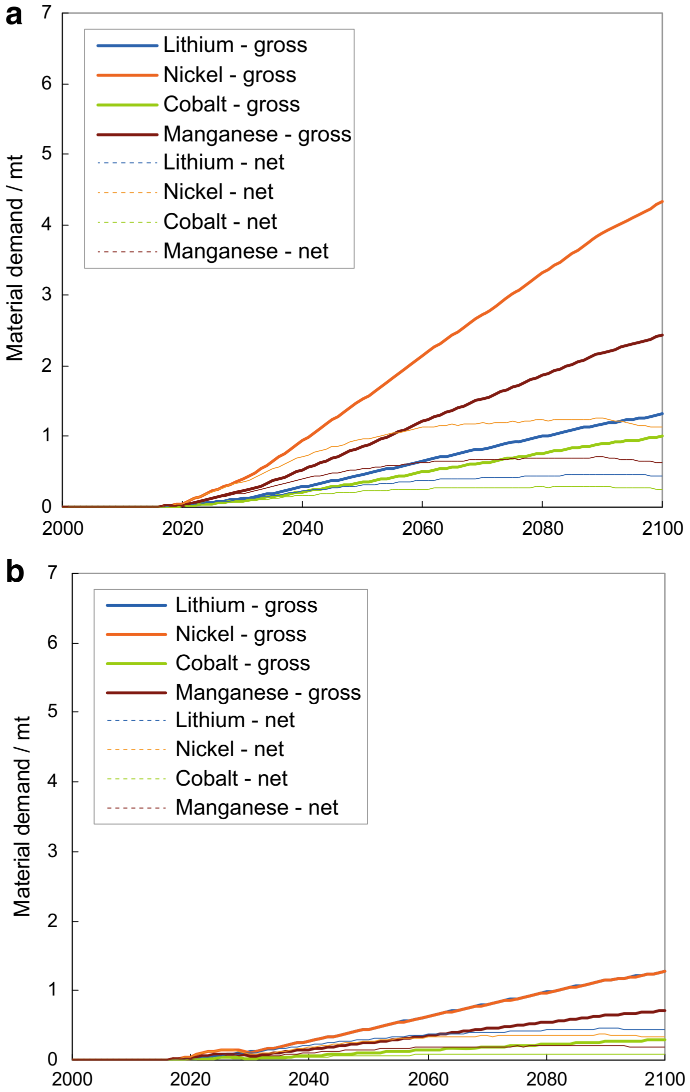

Fig. 6.5 Demand for critical metal resources in **a** S1 scenario, **b** S2 scenario, **c** S3 scenario

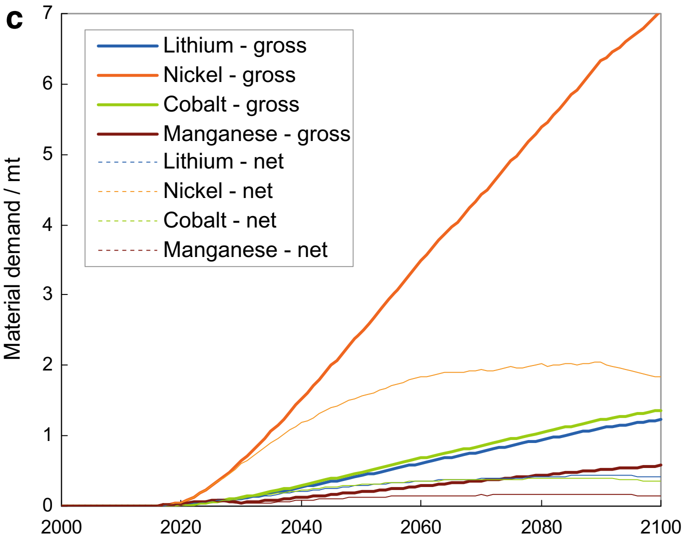

Fig. 6.5 (continued)

up over 80% of materials needed. Mainstreaming NCA technology will inevitably push up demand for nickel. In such scenario, the global primary mining exploitation to meet the net demand for lithium, nickel, cobalt and manganese shall be 554%, 89%, 300% and 1% of that in 2018 respectively.

6.2.3 Sustainability Analysis of Metal Resources

Table 6.2 lists the accumulative gross demand, recycling and net demand for critical metal resources across the world in all three scenarios till 2100. It should be clarified, though, that the net demand is calculated based on the assumption that recycling in any region only takes place within the region and the secondary resources thus acquired are intended to meet the demand of the region only. In the three scenarios, the global accumulative gross demand for lithium, nickel, cobalt and manganese respectively totalled 52.6 mt, 51.0 mt and 49.4 mt for lithium; 173.1 mt, 51.5 mt and 280.7 mt for nickel, 40.0 mt, 11.9 mt and 54.6 mt for cobalt and 97.6 mt, 29.0 mt and 23.5 mt for manganese. Recycling plays a central role in cutting and offsetting demand for primary resources by 26.5 mt, 25.7 mt and 24.9 mt respectively for lithium, 98.1 mt, 29.4 mt and 158.8 mt for nickel, 22.7 mt, 6.8 mt and 30.9 mt for cobalt, and 55.3 mt, 16.6 mt and 13.4 mt for manganese. In the three scenarios, the net accumulative demand for the four metals amounts to 26.1 mt, 25.3 mt and 24.5 mt respectively for lithium, 75.1 mt, 22.1 mt and 121.9 mt for nickel, 17.3 mt, 5.1 mt and 23.7 mt for cobalt and 42.3 mt, 12.5 mt and 10.0 mt for manganese.

Table 6.2 Accumulative impact on critical resources in different regions

	Scenario	S1				S2				S3			
	Metal	Li	Ni	Co	Mn	Li	Ni	Co	Mn	Li	Ni	Co	Mn
Inflow (Gross demand)	NAM	7.7	25.3	5.8	14.2	7.4	7.6	1.8	4.3	7.2	40.9	8.0	3.5
	WEU	6.1	20.1	4.6	11.3	5.9	6.0	1.4	3.4	5.7	32.5	6.3	2.8
	POECD	2.0	6.7	1.5	3.8	2.0	2.0	0.5	1.1	1.9	10.9	2.1	0.9
	EAS	7.8	25.5	5.9	14.4	7.5	7.8	1.8	4.4	7.3	41.3	8.0	3.6
	SAS	8.1	26.6	6.2	15.0	7.9	7.9	1.8	4.4	7.6	43.2	8.4	3.5
	PAS	4.7	15.6	3.6	8.8	4.6	4.6	1.1	2.6	4.5	25.5	5.0	2.1
	LAM	5.2	17.2	4.0	9.7	5.1	5.0	1.2	2.8	4.9	28.0	5.4	2.3
	EIT	1.7	5.5	1.3	3.1	1.6	1.6	0.4	0.9	1.6	8.9	1.7	0.7
	SSA	5.5	18.0	4.2	10.1	5.3	5.3	1.2	3.0	5.1	29.2	5.7	2.4
	MNA	3.8	12.7	2.9	7.1	3.7	3.7	0.9	2.1	3.6	20.6	4.0	1.7
	World	52.6	173.1	40.0	97.6	51.0	51.5	11.9	29.0	49.4	280.7	54.6	23.5
Outflow	NAM	5.0	16.6	3.8	9.4	4.9	5.0	1.2	2.8	4.7	26.8	5.2	2.3
	WEU	4.0	13.1	3.0	7.4	3.9	4.0	0.9	2.2	3.7	21.2	4.1	1.8
	POECD	1.4	4.5	1.0	2.5	1.3	1.4	0.3	0.8	1.3	7.2	1.4	0.6
	EAS	5.5	18.2	4.2	10.2	5.4	5.6	1.3	3.2	5.2	29.3	5.7	2.6
	SAS	5.1	16.8	3.9	9.4	5.0	4.9	1.1	2.8	4.8	27.2	5.3	2.2
	PAS	2.8	9.3	2.2	5.3	2.7	2.7	0.6	1.5	2.7	15.2	3.0	1.2
	LAM	2.9	9.6	2.2	5.4	2.8	2.8	0.7	1.6	2.7	15.6	3.0	1.3
	EIT	1.0	3.3	0.8	1.9	1.0	1.0	0.2	0.5	0.9	5.4	1.0	0.4
	SSA	3.1	10.4	2.4	5.8	3.1	3.1	0.7	1.7	2.9	16.8	3.3	1.4
	MNA	2.2	7.3	1.7	4.1	2.1	2.1	0.5	1.2	2.1	11.8	2.3	1.0
	World	33.1	109.0	25.2	61.4	32.1	32.6	7.5	18.4	31.1	176.5	34.4	14.9
Recycled	NAM	4.0	14.9	3.5	8.4	3.9	4.5	1.0	2.6	3.8	24.1	4.7	2.1
	WEU	3.2	11.8	2.7	6.6	3.1	3.6	0.8	2.0	3.0	19.1	3.7	1.6
	POECD	1.1	4.0	0.9	2.3	1.1	1.2	0.3	0.7	1.0	6.5	1.3	0.6
	EAS	4.4	16.4	3.8	9.2	4.3	5.0	1.2	2.8	4.2	26.4	5.1	2.3
	SAS	4.1	15.1	3.5	8.5	4.0	4.5	1.0	2.5	3.8	24.4	4.8	2.0
	PAS	2.3	8.4	1.9	4.7	2.2	2.5	0.6	1.4	2.1	13.7	2.7	1.1
	LAM	2.3	8.6	2.0	4.9	2.3	2.5	0.6	1.4	2.2	14.0	2.7	1.2
	EIT	0.8	3.0	0.7	1.7	0.8	0.9	0.2	0.5	0.8	4.8	0.9	0.4
	SSA	2.5	9.3	2.2	5.3	2.4	2.7	0.6	1.5	2.4	15.1	2.9	1.2
	MNA	1.8	6.6	1.5	3.7	1.7	1.9	0.4	1.1	1.7	10.7	2.1	0.9
	World	26.5	98.1	22.7	55.3	25.7	29.4	6.8	16.6	24.9	158.8	30.9	13.4
Net demand	NAM	3.6	10.3	2.4	5.8	3.5	3.0	0.7	1.7	3.4	16.8	3.3	1.4
	WEU	2.9	8.3	1.9	4.7	2.8	2.4	0.6	1.4	2.7	13.4	2.6	1.1

(continued)

Table 6.2 (continued)

	Scenario	S1				S2				S3			
	Metal	Li	Ni	Co	Mn	Li	Ni	Co	Mn	Li	Ni	Co	Mn
	POECD	0.9	2.7	0.6	1.5	0.9	0.8	0.2	0.4	0.9	4.3	0.8	0.4
	EAS	3.3	9.2	2.1	5.2	3.2	2.7	0.6	1.5	3.1	14.9	2.9	1.2
	SAS	4.0	11.6	2.7	6.5	3.9	3.4	0.8	1.9	3.8	18.7	3.6	1.5
	PAS	2.5	7.2	1.7	4.1	2.4	2.1	0.5	1.2	2.3	11.8	2.3	1.0
	LAM	2.9	8.6	2.0	4.8	2.8	2.5	0.6	1.4	2.7	13.9	2.7	1.1
	EIT	0.9	2.5	0.6	1.4	0.8	0.7	0.2	0.4	0.8	4.1	0.8	0.3
	SSA	2.9	8.7	2.0	4.9	2.9	2.6	0.6	1.4	2.8	14.1	2.7	1.2
	MNA	2.1	6.1	1.4	3.4	2.0	1.8	0.4	1.0	1.9	9.9	1.9	0.8
	World	26.1	75.1	17.3	42.3	25.3	22.1	5.1	12.5	24.5	121.9	23.7	10.0

This study defines the ratio between primary resources exploitation associated with the above net demand and the currently identified resources as demand-reserve ratio, which is respectively 47%, 45% and 44% for lithium, 64%, 19% and 104% for nickel, 82%, 24% and 112% for cobalt and 8%, 2% and 2% for manganese in the three scenarios, as illustrated in Fig. 6.6. From the perspective of sustainable supply of resources, the demand-reserve ratio for lithium is close to 50% in all three scenarios, implying considerable pressure of its sustainable supply. In addition, the demand for lithium is rather inflexible, as the resource is essential to the current mainstream battery technologies. Its limited availability will be the key impediment to the scale-up of EVs until any breakthrough is made in the next generation battery technologies such as metal-air. A common trait of nickel and cobalt is that their demand-reserve ratio will both exceed 100% in the extreme situation of NCA scenario, which signals

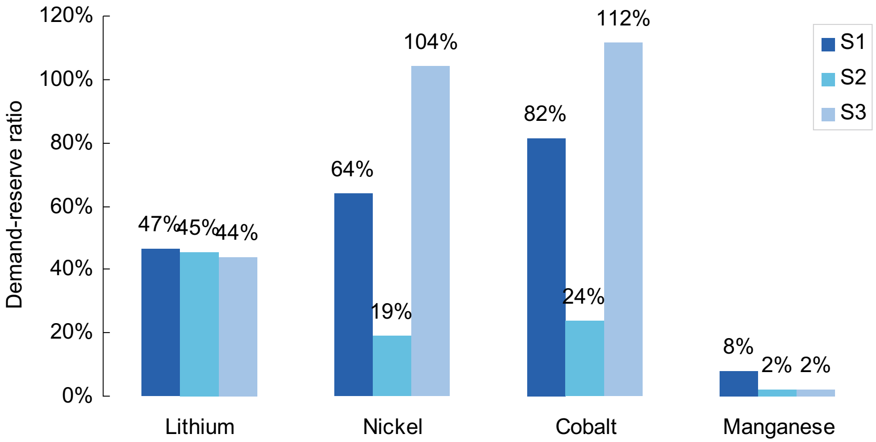

Fig. 6.6 Demand-reserve ratio of Lithium, Nickel, Cobalt and Manganese

a grim outlook in the sustainable supply of resources. However, in the LFP scenario, such ratio for both metals is brought to a low level, meaning that demand for nickel and cobalt is rather flexible and the challenge in the sustainable supply can be circumvented by a wise planning of technological options. The demand-reserve ratio for manganese is low in all three scenarios; moreover, EVs are not major consumers of manganese, which produces no constraint on EV market expansion.

It should be noted, however, that all the above analysis is based on the impact of electrification of light-duty vehicles, with no assessment on resources demand from the electrification of heavy-duty vehicles or sectors other than transportation. As battery has become the main consumer of lithium and cobalt, the analysis in this research could largely capture the future supply and demand of the resources. But the massive application of nickel in stainless steel and other areas will generate complex interactions with its application in EVs, which is not covered by this research, and is thus a limitation.

6.3 Supply Risk Assessment

6.3.1 Meaning of Supply Risk

Since the beginning of the century, the next generation clean energy aiming at efficient energy use while cutting GHG emissions has aroused public attention and has been on a fast track of development. As one of the typical products of clean energy technology, lithium battery is gaining increasing popularity due to better performance in power intensity and service life since 1991 when Sony started its commercialization. First applied in consumer electronics such as mobile phones and computers, lithium battery quickly took over nickel-metal hydride battery and nickel-cadmium battery, and became the biggest contributor to the commercialization of EVs. Now, lithium battery represents the most commonly used electrochemical energy storage device in 3C electronics, EVs and power grid, etc. The shipment of battery used in EVs has surged from 1.08 GWh in 2011 to 106 GWh in 2018, nearly a 100 times within 8 years. It is widely estimated that the continuous replacement of combustion engine vehicles by EVs will trigger a spike in market demand for lithium battery by 10–20 times.

The precondition of the exponential growth of lithium battery consumption is a stable upstream supply chain, especially that of the raw materials. Lithium battery is composed of cathode materials, anode materials, separator and electrolyte, of which cathode materials largely determine battery performance and account for the biggest share in the cost. The core raw materials for producing lithium battery cathode include lithium, cobalt, nickel and manganese.

Compared to conventional staple metal commodities (e.g.: iron and aluminum), the supply of these materials faces multiple potential challenges such as oligopoly, low recycling rate, policy instability, noticeable environmental and social risks. It is estimated that 15–20% of cobalt mining in DRC comes from artisanal mining, often by women and children. The Centre for Research on Multinational Corporations estimated that 40,000 children work in underground tunnels, without basic safety equipment. In addition, due to a lack of preventative measures, lots of cobalt miners have extremely high levels of toxic metals in their body, which could cause them more susceptible to respiratory illness, heart disease, or even cancer. Mining of lithium in Chile has been in dispute for depleting local groundwater resources across the Atacama Desert, which destroys ecosystems and converts meadows and lagoons into salt flats. Refining of nickel presents a similar problem, such as the tailings out of nickel HPAL operations in Indonesia that may be dumped into deep sea, challenging ocean environment with potential spills.

The high potential risks give rise to public concerns over the stable reserves and production of these metals to meet the growing consumption needs of lithium battery products. By now, many assessments and diagnoses have been conducted on the sustainable supply of resources associated with lithium battery. Criticality assessment is a commonly used method in answering such questions, aims at identifying materials of high supply risk and those significant for the economic system, which can be understood as supply risk in a broad sense. The methodological framework normally consists of three dimensions: supply risk, environmental impact and vulnerability of the system to the supply disruption (Graedel et al. 2015). Each dimension comprises multiple geographical, socio-economic and environmental indicators. The criticality of materials associated with lithium battery has been assessed in numerous studies. Olivetti et al. calculated the content of various metals in the lithium battery and compared the scale of supply constraints of these metals (Olivetti et al. 2017). Helbig et al. rated the supply risk of lithium battery based on 11 indicators (Helbig et al. 2018); while Dehghani-Sanij et al. came up with the environmental impact of various energy storage systems, including the impact of lithium battery (Dehghani-Sanij et al. 2019).

Despite a litany of research, some gaps still exist in these studies. In the current assessment, indicators adopted mainly focus on the mineral production stage because all materials considered are in mineral type, with no regard to the supply risk of lithium battery materials in the downstream processing stages of the supply chain. One of the reasons is that the methodology for resources criticality assessment was developed on fossil fuels and bulk consumption materials before expansion of the research to new materials for innovative technologies. Another reason is that the distribution of mineral supply is mainly driven by resources endowment and prone to natural disasters. Compared to downstream processing, mining is less influenced by human activities. This explains why this phase where less human intervention is found has captured more attention.

Yet it should be noted that metallic minerals and fossil energy are utilized in vastly different ways. Trading of fossil fuels only takes place in the first stage of energy supply chain, and downstream processing and consumption usually occurs within certain countries and regions. On the contrary, a more dispersive supply chain exists with the consumption of mineral resources from primary extraction to final utilization, where international trade can be conducted in any stage of processing. In the context of economic globalization, differences between upstream and downstream prevail in the distribution of raw materials supply. Besides, risk management of humans is limited during processing. For instance, a clear approach to decentralize the supply is to relocate production capacity concentrated in a handful of countries to a wider range. However, such approach is flawed by accommodating risk reduction in material supply only. In the real world, capacity relocation involves a mixture of political, social and economic factors and requires overall consideration of impact on domestic employment, rising cost of production and sunk cost, etc. Therefore, in defining the supply-centered strategy, hidden risks in the processing stage of the supply chain should not be ignored. Systematic assessment of supply risks and their corresponding impact in each stage of the supply chain is crucial, especially for long term strategic decisions.

6.3.2 Method of Supply Risk Assessment

In order to fill this gap, we have developed a supply risk index of lithium battery industry (SRIL) which consists of two dimensions: the probability of supply disruption and the impact of materials on lithium battery industry. The quantification of supply disruption probability is based on Herfindahl-Hirschman Index (HHI) and World Governance Indicator (WGI) of the World Bank. HHI is the most commonly used in calculating market concentration: the higher its value, the more concentrated the market, and the higher probability of supply disruption. WGI is annually updated by the World Bank to reflect the impact of governance level of different countries on the probability of supply disruption. The average WGI value from 1996 to 2017 is used in this study to mitigate the influence of unexpected incidents and statistical errors. Based on these two indexes, the supply disruption probability index, HHI-WGI, is calculated with Formula (6.1).

$$\mathrm{HHI\_WGI} = \sum_{\mathrm{i}} \mathrm{S}_{\mathrm{i}}^{2} * \mathrm{WGI}_{\mathrm{i}} \tag{6.1}$$

S_{i} is the share of country *i* in total supply (in %); $\mathrm{WGI}_{\mathrm{i}}$ is the governance indicator of country *i*.

The impact of materials on lithium battery industry is quantified with "vulnerability index", which describes the impact of materials on both supply and demand side. On the supply side, the share of material consumed by the lithium battery industry in the total use of such material is defined as α, which indicates the impact of lithium battery market on material supply. On the demand side, "contribution factor" is proposed to quantify the role of materials in lithium battery industry. Currently, lithium battery can be grouped into five categories by cathode material: NCM, NCA, LCO, LMO, and LFP. The production share of each type of cathode material is used to show its contribution to the lithium battery market β (where equivalent weight unit of lithium is used in all output data), and the contribution factor of each material is defined as the aggregate of the total share of its cathode material output. For instance, the contribution factor of cobalt is the combined share of NCM, NCA and LCO output. Based on the above data, the vulnerability index of material x is calculated with Formula (6.2).

$$\mathrm{V_x} = \frac{\log_{10}(\alpha_\mathrm{x} * \beta_\mathrm{x} + 1)}{\sum \log_{10}(\alpha_\mathrm{x} * \beta_\mathrm{x} + 1)} \tag{6.2}$$

Finally, SRIL of material x in lithium battery production is calculated based on supply disruption probability index HHI-WGI and vulnerability index V, with Formula (6.3).

$$\mathrm{SRIL_x} = \mathrm{HHI\_WGI_x} * \mathrm{V_x} \tag{6.3}$$

6.3.3 Results of Supply Risk Analysis

Figure 6.7 illustrates the supply concentration of four critical materials of lithium battery in varied stages. The higher HHI and HHI-WGI values, the more concentrated the supply. Three stages are delineated for the supply chain of all four materials: mining, refining and manufacturing. The figure shows that supply concentration differs among various stages. From the perspective of HHI, the concentration of lithium and cobalt features a steady increase from mining to refining and product manufacturing; while a drop is detected for nickel and manganese. From the perspective of HHI-WGI, the supply risk differs considerably among different processing stages. From upstream to downstream, HHI-WGI decreases for cobalt while increases for lithium, nickel and manganese. HHI-WGI of cobalt exploitation and manganese manufacturing is markedly higher than other stages. The results show that mining should be the greatest concern for cobalt while higher risk in downstream processing should be noticed for lithium, nickel and manganese.

Figure 6.8 reveals the SRIL value of all four materials in the supply chain. For lithium battery industry, the relative magnitude of supply risk is consistent for the four materials in three processing stages. Compared to other metals, cobalt is subject to the greatest hidden supply risk, followed by lithium and manganese; while the supply risk of nickel has always been the least significant. By the average SRIL value, material supply risk peaks in the manufacturing stage, followed by refining and mining. A horizontal comparison of supply risk of all materials in different stages reveals the highest risk of cobalt in mining, refining and manufacturing, lithium in refining and manufacturing, and manganese in manufacturing.

The significance of this study is to quantifiably identify the key stakeholder in the supply chain of metal resources. Based on the above results, the corresponding strategic plan can be deployed to mitigate material supply risk in lithium battery industry. A systematic production capacity planning from multiple dimensions is needed for stakeholders in the battery industry. Manufacturers tend to prioritize production cost for the sake of maximum revenue; however, it should be recognized

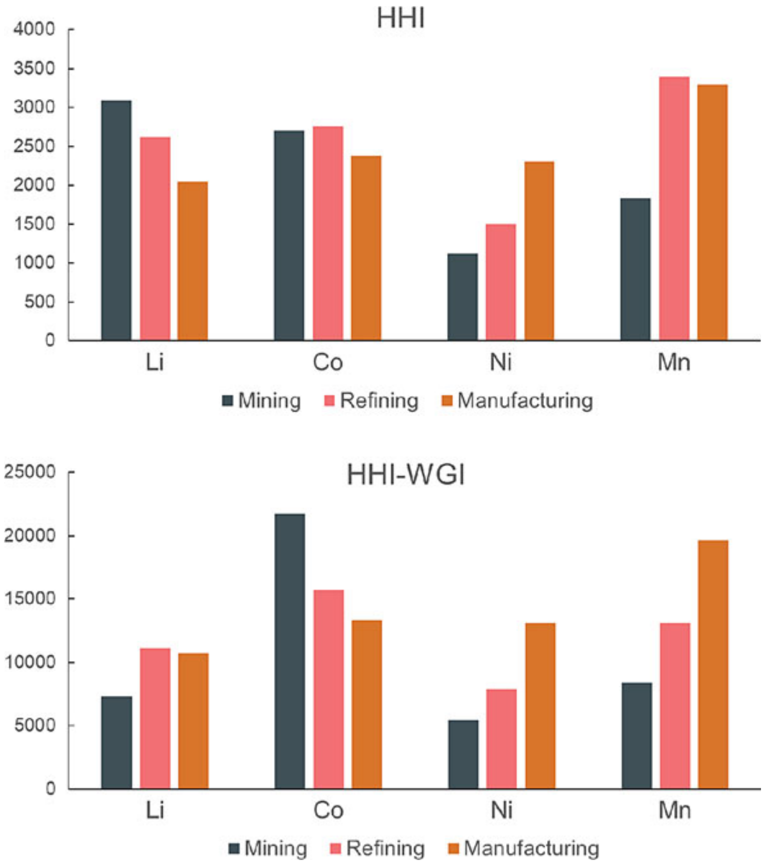

Fig. 6.7 HHI and HHI-WGI index for four critical materials in Lithium battery (as directly cited from the source literature). *Note* refer to Formula (6.1) for the meanings of HHI and HHI-WGI

that the precondition for profit is the stable raw material supply. To this end, a more dispersed distribution of production capacity is essential. In this regard, our study points to the necessity to prioritize mining, metallurgy and production of lithium and cobalt, refining and production of manganese and manufacturing footprint of lithium battery.

It should be recognized that the distribution of production capacity in any stage is not static. Drivers of exploitation, processing and final consumption are different but all dynamic. The distribution of the mining footprint mirrors the regional resources endowment in some measure, and can be reversed through investing in deposit prospecting and mining technology progress. The processing capacity reflects the industrialization level of a region, and production capacity will undergo radical shift with industrial restructuring and changes in market mechanism. Final consumption is mainly subject to the impact of population, national economy and consumption tendency. The action mechanisms of these variables usually function inside a country.

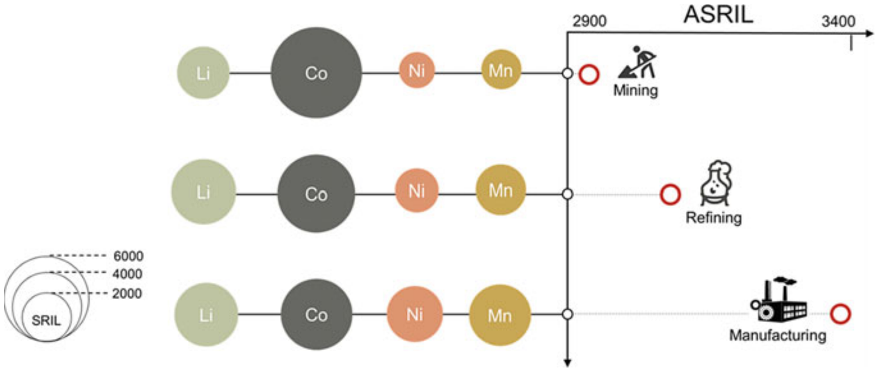

Fig. 6.8 Supply risk in industrial chain of Lithium battery (as directly cited from the source literature). *Note* the size of the bubbles on the left represents the SRIL value in each stage of the industrial chain of the four metals, and is proportional to SRIL value. The values in the coordinates on the right indicate the average SRIL in mining, refining and manufacturing. Refer to Formulas (6.1)–(6.3) for the calculation method of SRIL

Apart from these variables, the force of overseas investment is not to be neglected. The finite natural and human resources in China would prompt many enterprises to move their capacity overseas through M&A and factory building. For instance, most of lithium battery and anode material capacity in China was transferred from Japan and South Korea; while a large bulk of cobalt mines in DRC and lithium mines in Australia are owned by Chinese companies. The investing country should also share the responsibly of supply risk control with countries if conditions permit. Changes in the supply structure of single production stage would require adjustments of the structure in other stages to ensure the sustainability of resources utilization.

6.4 Policy Implications

It can be concluded from this study that EVs in the future call for huge amount of metals like lithium, nickel and cobalt, incurring potential pressure and risk of supply. This would require governments and industries to rethink key strategic issues such as the footprint of industrial chains, strategic reserves of resources, resources recycling, battery technology development, etc.

This study reveals that the battery industrial chain has spread all over the world, with enormous global trade in any given part of the chain, plus concentration of supply to various extent. In the surging tide of economic globalization, a global industrial chain contributes to higher efficiency and lower production cost. Nevertheless, globalization of industrial chain is accompanied by a strong dependence on imported resources and products in some countries and regions, whose industrial chain can be fatally vulnerable to extreme conditions of interrupted supply due to epidemic and trade protectionism. This signifies that footprint of industrial chain should feature a balance of efficiency and supply risk control. Battery industrial chain, for example, covers critical resources exploitation, primary/secondary composite production, cathode and anode materials/separator/electrolyte production, battery manufacturing, etc. While expanding global industrial chain, all countries should identify critical supply risks along the chain in light of their own conditions, and build domestic production capacity as appropriate to avoid excessive concentration of the risks. In particular, for products with geographical immobility such as primary mineral resources, countries and regions with great demand for these critical metals should consider building proper strategic reserves to buffer the shock from potential supply disruption on the industrial chain.

This study shows that technology options produce decisive impact on critical resources demand. Technology options represented by NMC battery will spark soaring demand for lithium, nickel and cobalt; while technologies represented by LFP can ward off excessive demand for nickel and cobalt. In this light, a wise choice of battery technology is crucial for the sustainable development of EVs. As varied battery technologies vary in cost, energy density, safety, service life and material demand, the choice should be based on comprehensive consideration of various factors. Despite the advantage of LFP in resource sustainability, its energy density is lower than NMC; in particular, its volumetric energy density is the main barrier holding back its application in light-duty vehicles. This calls for technological innovation to overcome its weakness for wider application. For example, the blade battery of BYD has dramatically enhanced the volumetric energy density of LFP battery, which is vital for technology scale-up. Meanwhile, the next generation battery technologies, in particular metal air, are expected to remove the trouble of resource shortage. Yet the inherent technological uncertainty requires follow-up on its development and support in R&D and demonstration.

This study demonstrates that resources recycling is an effective means to ramp up secondary supply and reduce demand for primary mineral resources. This study assumes that the recycling rate of critical metal resources shall see a sharp rise in the next decade and reach a fairly ideal level; but in reality, multiple challenges still exist in battery recycling. First, the approaching retirement boom of EVs will create an enormous amount of retired batteries, which requires rapid development of infrastructure to cope with the surging demand; meanwhile, regulatory framework for retirement needs continuous revision to ensure the effectiveness of recycling. This presents challenges to recycling network expansion, design of policy measures and innovation in recycling technologies. Second, currently available recycling technologies include pyrometallurgical method, hydrometallurgical method, physical recycling, etc., all of which are under development. The sophistication of such technologies determines the cost and incentives of recycling companies. But the current recycling rate of lithium is close to zero. In order to turn around the situation, recycling technologies with high efficiency and low cost are indispensable, and massive innovation is needed. Third, globalization of the EV industrial chain suggests that manufacturing, use and retirement of battery may take place in different countries and regions; in this connection, sharing of battery technical data becomes crucial for effective recycling, which entails effective follow-up management on a global scale.

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Chapter 7
Development of Low Carbon Technology in China's Iron and Steel Industry

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Abstract As iron and steel production features high energy consumption and massive GHG emissions, the low carbon development of the industry is crucial for China's INDC target. Multi-pronged measures should be taken to grapple with the problems with the industry to secure low-carbon green development. In terms of technical solutions for the low-carbon development of the industry, improvement is more likely on both the consumption and the production side. In terms of zero carbon technology of iron and steel production, hydrogen steelmaking and CCUS are among the few technical options for zero carbon development of the industry. It's advised to enhance the overall management of China's iron and steel industry both on the production and the consumption sides, promote R&D and application of new technologies for process improvement, make technological preparations for the recovery and recycling of steel scraps and short process steelmaking. In the long run, theoretical research, strategic analysis and construction planning is necessary for CCUS-hydrogen steelmaking as the goal, in a bid to facilitate the restructuring of China's energy mix and achieve close to zero emissions in the industry. Before zero emission it will take long time for steel industry to transit. Step abatement of CO_2 emission by technical innovation still is a main focus for most steel works.

Keywords Iron and steel industry · Deep decarbonization · Energy consumption · Greenhouse gas

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7.1 Current Development of China's Steel Industry and Its Carbon Emission Trend

7.1.1 Steel Production and Consumption

As one of the biggest industrial sources of CO_2 emissions, iron and steel industry contributes approximately 28% of direct GHG emissions from industrial sectors globally. China's growing industrialization and urbanization mean that its iron and steel output will stay at the current high level for long time. As is illustrated in Fig. 7.1, since 2012, China has produced nearly half of the world's steel and more than half of the world's iron, which made carbon reduction all the more important for the industry in the country. In 2018, its crude steel output exceeded 900 Mt, making the industry one of the principal carbon emission sources of China and the world at large.

China Iron and Steel Industry Yearbook 2019 has listed the main products of China's iron and steel industry: in 2018, the annual output totaled 928 Mt for crude steel, a YOY increase of 6.6%; 771 Mt for pig iron, 1106 Mt for finished steel products. The apparent consumption of crude steel stood at 871 Mt; the net export of crude steel was 57.425 Mt, accounting for 6.19% of its total output. In 2018, China imported 1.064 billion tons of iron ores, accounting for 85% of the total consumed iron ores, very high reliance on seaborne iron ores. Imported iron ores are mainly from Australia (679 Mt), Brazil (234 Mt), South Africa (41 Mt), India (15 Mt) and Iran (15 Mt) at an average FOB price of 70.96 USD/ton. As is shown in Fig. 7.2, China represented 52% of the world's steel production in 2018. As far as steel consumption is concerned, China consumed approximately 740 Mt of finished

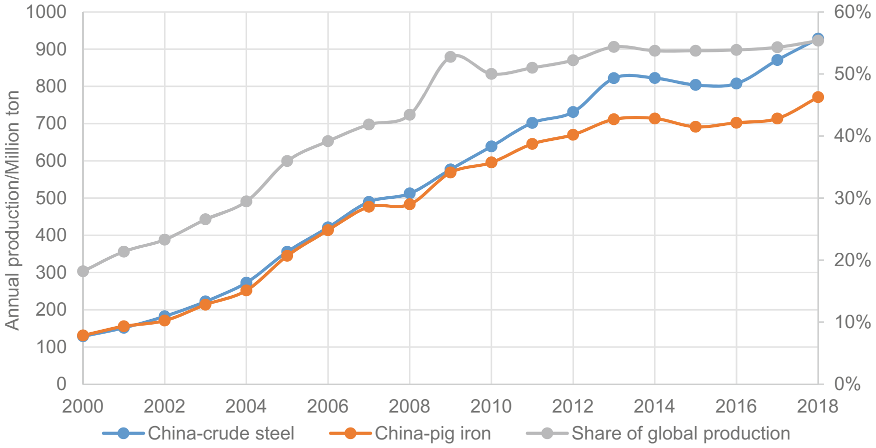

Fig. 7.1 China's annual crude steel and pig iron output and share of global production (Units: Mt). *Source* Official website of the world steel association (WSA) www.worldsteel.org

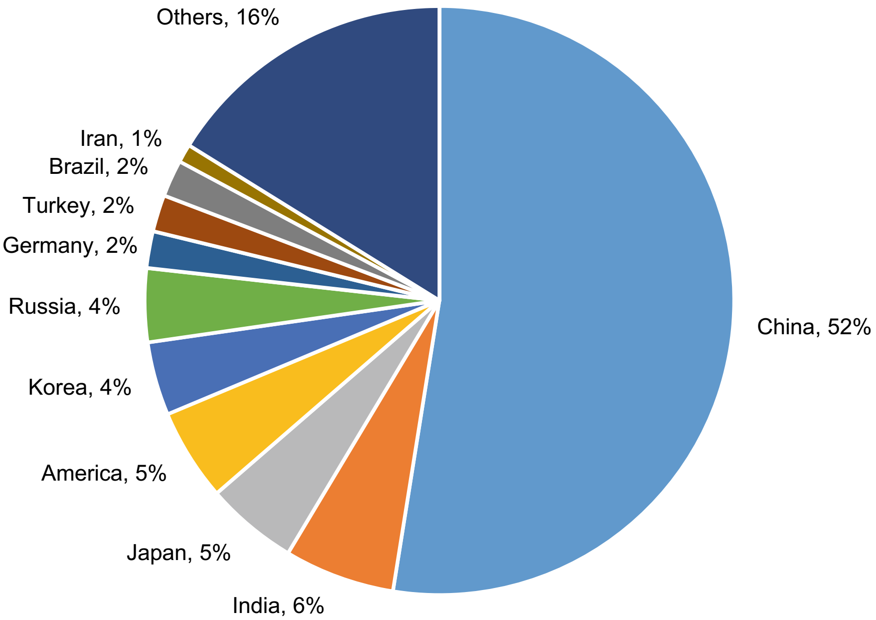

Fig. 7.2 Share of steel output in major steel producing countries in 2018. *Source* Official website of WSA, www.worldsteel.org

iron and steel products in the same year (Editorial Board of China Iron and Steel Industry Yearbook 2020).

In China, iron and steel industry made up approximately 15% of the country's total CO_2 emissions in 2017 (Energy Transitions Commission (ETC) 2019). The completion of China's urbanization will result in less demand from the construction sector for steel, and more steel materials would come from recycling of scraps, promising a lower proportion of iron and steel industry in carbon emissions. Besides, there is still potential for improving energy efficiency of iron and steel production adopting the best available technology (BAT). But to achieve zero emissions of the sector, China needs to embrace more radical decarbonization technologies in long process iron and steel production.

In 2015, Beijing-Tianjin-Hebei region and the Yangtze River Delta, both being iron and steel producing hubs in China, accounted for 26.0% and 17.9% respectively in the country's total crude steel output. Large and medium size iron and steel plants (a.k.a. the China Iron and Steel Association (CISA) members) made up 78.8% of the total while SMEs (a.k.a non-CISA members) comprised 21.2%. Iron and steel industry feature massive production, enormous materials handling, vast input and output of materials and energy during production and release of tremendous GHG and pollutants (Liu 2016).

Energy consumed by the industry mainly includes coal, coke, electricity, natural gas, etc., making it a typical sector of high energy consumption and high emission. In

2015, China's iron and steel industry consumed 639.51 Mt of standard coal, or 14.9% of total energy used nationwide, of which coal and coke combined stood at around 89.9% while electricity and natural gas at 10.1%. Over the last decade, the share of iron and steel industry in the country's total energy consumption ranged between 14.9 and 19.4%, an annual average of 16.6%. The progress of industrialization and urbanization in China is expected to be accompanied by surging energy consumption of the industry and consequently, mounting pressure of GHG emissions (Liu 2016).

The preceding paragraphs have revealed the following traits of China's iron and steel industry:

(1) Rapid development. For several consecutive years, China has topped the world in annual iron and steel output and is capable of producing over 1000 varieties of steel, and rolling and processing over 40,000 different specifications of steel products. Meanwhile, the conformity rate of products has reached 85%, with the quality of some products measuring up to advanced international standards.
(2) Swift upgrade of production processes. China's iron and steel industry is seeing continuous technical innovation, phasing out obsolete technologies and outdated installations, as evidenced by the elimination of open-hearth steelmaking in all steel plants.
(3) Bright prospects thanks to China's growing economy and world economic recovery, and the government macro regulation and control of the industry plays a key role.

On the other hand, however, China's iron and steel industry is not without its weaknesses:

(1) The deconcentrated industrial footprint falls short of the demands of economy of scale. Among the existing steel plants in China, only 70 have an annual output of over 1 Mt. In contrast, almost all the iron and steel production in France is managed by one company—Usinor. This demonstrates China's insufficient concentration of production compared to developed countries, which, in some measure, eroded the international competitiveness of China's iron and steel sector.
(2) Lack of technical specialization. Currently, iron and steel enterprises in China are capable of producing a wide spectrum of products with all specifications and types, but very few flagship products are offered, and the market segmentation remains rather fuzzy at the national level due to a lack of technical specialization. In comparison, specialized division of labor is crystal clear in most iron and steel plants in developed countries, with market segmentation basically shaped among producers on the national level and even worldwide. The obsolete technical equipment in steel and iron industry in China and insufficient concentration and specialization have resulted in the alarming inefficiency and high cost of iron and steel products in China.
(3) The gap in overall quality of the industry does not only exist between China and developed countries but also with developing countries in terms of cost

efficiency. Currently, China's steel output per capita is only 32% of the world's average or even lower; while the man-hour per ton of steel is 6 times higher than that of developed countries, hence barely any comparative advantage in terms of production cost.

7.1.2 Production Procedures and Emission Features

As is illustrated below, the production of iron and steel consists of multiple procedures and equipment such as raw materials system, sintering, pelletizing, coking, ironmaking, steelmaking, rolling and public auxiliary system. By technical category and corresponding raw materials used in furnaces, four groups of modern iron and steel production routines are identified, namely blast furnace-basic oxygen furnace (BF-BOF), steel scrap- electric arc furnace (steel scrap-EAF), direct reduction-electric arc furnace (DR-EAF) and COREX-BOF (Huang 2016), which are categorized into long process and short process, with procedures shown in Fig. 7.3.

Long process iron and steel production (BF-BOF).

The long process iron and steel production is characterized by conventional techniques with multiple procedures starting from iron ores, primarily with BOF at the core. The main material is usually iron ore and a small quantity of iron and steel scraps, with coking coal as the reduction agent. The process flow of long process is: iron ore mining—ore dressing (most ores are raw ores)—coking—production of artificial lump ore by agglomerated (sintering and pelleting)—BF ironmaking (hot metal)—BOF (EAF in some cases) steelmaking—secondary refining until the liquid steel meets requirements on chemistry and temperature—slab or billet made by casting—steel products by rolling. Long process steelmaking has the following features:

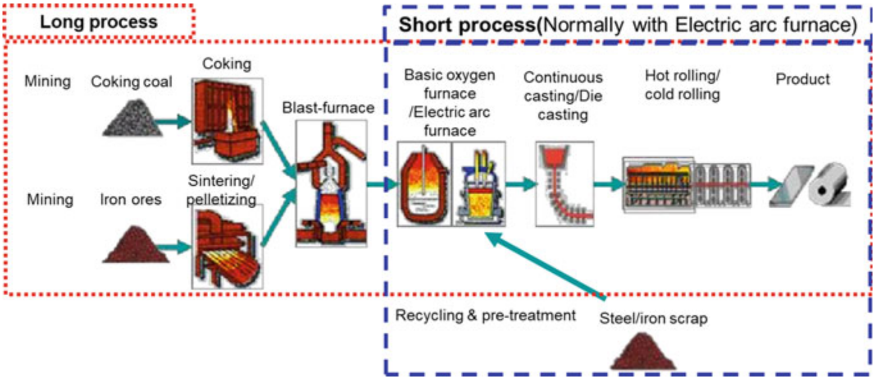

Fig. 7.3 Typical steelmaking procedure. *Source* Yun et al. 2006

(1) Multiple equipment and massive investment: typical iron and steel plants have an annual production capacity of over 4 Mt;
(2) Better endpoint control: the reaction of slag and steel is closer to the balance point than electric furnace;
(3) Long process features better purity and quality stability of hot steel: basic oxygen furnace with secondary refining ensures better performance, higher production rate and acceptable purity. This approach is mainly suitable for steel varieties of low carbon/ultra-low carbon and low residual elements, especially steel products in large quantities and lower alloy content;
(4) Larger output and faster production;
(5) Higher energy consumption and multiple sources of pollution: the massive energy consumed in the steelmaking process mainly comes from the chemical reaction between oxygen and elements prone to oxidation in the steel;
(6) Lack of flexibility of the technical process: dependent on fossil fuels, unable to activate/deactivate instantly, not suitable for alloy of high melting point in small and medium scale production such as high alloy steel, alloy tool steel, refractory ferrotungsten, etc.

Short process steelmaking with electric arc furnace.
With EAF at the core, short process starts with iron and steel scraps with less production procedures. Steelmaking with EAF is an approach that uses the electric arc thermal effect for metal smelting, especially high alloy steel, with steel scrap or iron from other sources as the feed. The production procedures of short process include: recycling of steel scrap—crushing, dressing and pre-treatment—steelmaking by electric arc furnace—secondary refining—various casting blanks from casting—rolling.

Compared to typical long process technical routine, short process approach skips sintering (pelletizing), coking and BF ironmaking, all of which contribute significantly to energy consumption, pollution and CO_2 emission. This approach reduces raw material and energy consumption and pollutant emissions by heaps and bounds, as illustrated in Fig. 7.4. Short process steelmaking has the following features:

(1) Less complicated equipment, shorter cycle of infrastructure construction and investment returns;
(2) EAF is essentially high-temperature steelmaking which is able to eliminate hazardous gases and inclusive while enabling deoxidation and desulfurization, hence capable of producing special steel of high quality;
(3) High industrial adaptability allowing intermittent production, with a specialized production system featuring automation, mechanization and low energy consumption, making it more competitive;
(4) Less heat loss and higher efficiency;
(5) Enjoying more benefits from clean power as electricity is the main energy source, making further carbon emission reduction an easier task;
(6) Temperature control remains a challenge, resulting in quality variation within finished products.

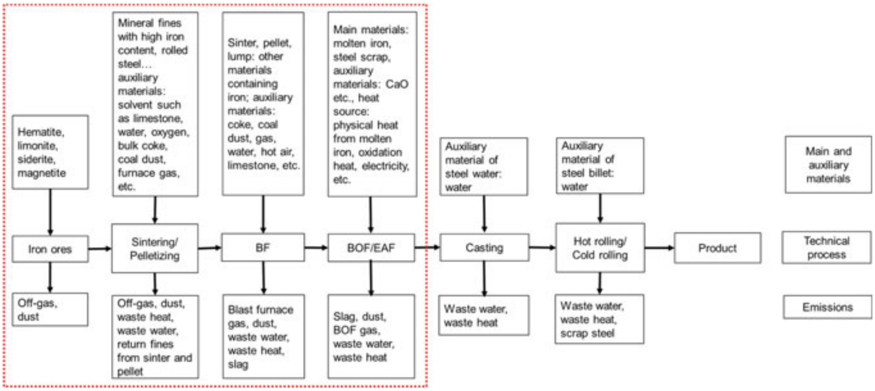

Fig. 7.4 Consumption of raw materials and auxiliary materials and emissions of long process and short process. *Source* Yun et al. 2006. Note Cases in red dotted lines indicate processes and material consumption eliminated by short process steelmaking

Current development and future prospects of long and short process steelmaking.

The proportion of short process steel in major steel producing countries is shown in Fig. 7.5. In 2018, China's crude steel production by long process totaled 820 Mt, i.e.

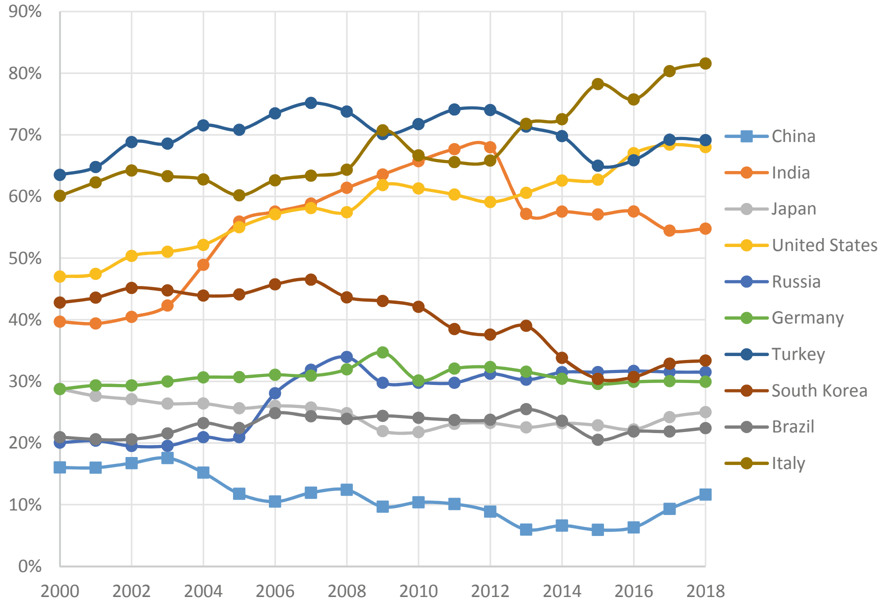

Fig. 7.5 Proportion of short process steel in top 10 crude steel producing countries. 2019 *Source* WSA

BOF steel accounting for 88.4%. 108 Mt were produced by short process, i.e. EAF steel making up 11.6%, as illustrated. Compared with the other top 10 crude steel producers such as Italy (EAF at 81.57%), US (EAF at 68.01%) and India (EAF at 54.78%), China ranks the lowest in short process steelmaking which is mainly used for high-end steel products for special purposes. Studies show that 2–2.15 tons of CO_2 will be released per ton of steel by BF-BOF while only 0.5 tons will be emitted by EAF. Objectively speaking, the low proportion of short process steel is a major contributor to the high energy consumption and carbon emission by China's iron and steel industry, and some scholars are calling for the shift from long process to short process steelmaking. However, the small share of short process in China has its realistic reasons, and it would be next to impossible to replace the long process directly by short process to align with developed countries in term of the share of EAF:

(1) High power cost making it difficult to reduce the cost of short process steelmaking;
(2) Short process steelmaking in China is not state of the art, with prevailing challenges such as high-power consumption;
(3) Iron and steel recycling and reusing is under developing in China;
(4) Iron and steel stock per capita is still growing in China while massive retirement of steel product has not taken place. The supply of scrap is limited in proportion of new demand for steel;
(5) As a "world factory", China has to meet the demand on products which are made from steel for numerous countries, steel demand still keeps strong; in other words, most of the long process steel plants which are able to produce enough steel are located in China, making the situation much different from Italy and other countries.;

Although it is unrealistic to build short process steelmaking facilities on a massive scale and align the share of short process steel with Italy or US in the near future, the following facts nonetheless provide reasons for optimism of its potential and value in China:

(1) The risk of overcapacity and excessive inventory. The rapid growth in iron and steel production/consumption in China indicates a surge in scrap in the future. Besides, policies of rapid absorption at the demand side (such as accelerating infrastructure construction) to tackle overcapacity are still valid, which stimulates iron and steel consumption but on the other hand increases risk of scrap oversupply. The succession of incidents sweeping across the world in the beginning of 2020 may shorten the market economic cycle and incur the risk of shrinking economy, and a new round of policy and economic incentives is likely to be applied in the global iron and steel industry, resulting in mounting pressure of steel scrap disposal in 2030 up to 2050;
(2) The risk of industrial transfer and contraction of international trade. As is stated above, China, known as "the world factory", produces products made from steel for multiple markets. However, the production cost in China may rise as

the economic growth continues; on the other hand, conservatism emphasizing industrial backflow is emerging in countries such as US; therefore, iron and steel industry faces the risk of relocation to underdeveloped regions and backflow to developed countries. Moreover, the series of events since the start of 2020 has aggravated the tension in international relations, which may produce a long-lasting impact on international trade. In this context, short process steelmaking can be a key technical option for China's iron and steel industry;

(3) The benefits of emission reduction brought by clean power. In light of the rapid development of renewable power, short process enables higher benefits of emission reduction brought by clean power compared to long process, which represents a critical technical option by iron and steel industry for China's INDC (IRENA 2018).

Therefore, despite the challenge of increasing the share of short process to the same level as developed countries, it is not only feasible but also necessary to develop short process steelmaking technologies, reduce the cost and build a comprehensive recycling system for scrap to ramp up production of short process. For the potential "scrap surge" and massive industrial transfer, short process steelmaking will provide a powerful solution to absorb scrap steel, secure iron ore resources and expand China's iron and steel market, with tremendous potential in its own rapid development and carbon emission reduction of iron and steel industry.

Apart from the shares of long and short process, the proportion of cold rolling, continuous casting and secondary refining also affect energy mix and consumption of iron and steel industry with indirect impact on CO_2 emissions, which will be discussed in the following paragraphs. In short, CO_2 emissions of iron and steel industry are closely linked with the techniques and production processes applied.

7.1.3 Emissions by Sector

7.1.3.1 Comprehensive Energy Consumption and Pollutant Emission of Iron and Steel Industry

A typical example of integrated production, iron and steel industry relies heavily on primary energy consumption, especially coal, featuring high energy intensity and high emission. It ranks among the major carbon-related industries and is a key contributor to global GHG emissions. As illustrated below, according to IEA statistics (Figs. 7.6 and 7.7), energy consumption of the industry saw steady growth in 2000–2017 from 18.32EJ to 33.44EJ, largely synchronous with the increase in global iron and steel output; meanwhile, the unit energy consumption of the industry slight decreased by 8% from 21.56 to 19.76 GJ/t. It should be noted that the production experienced a plateau of approximately 2 years due to the global economic plunge triggered by the sub-prime mortgage crisis in US at the end of 2008, delivering

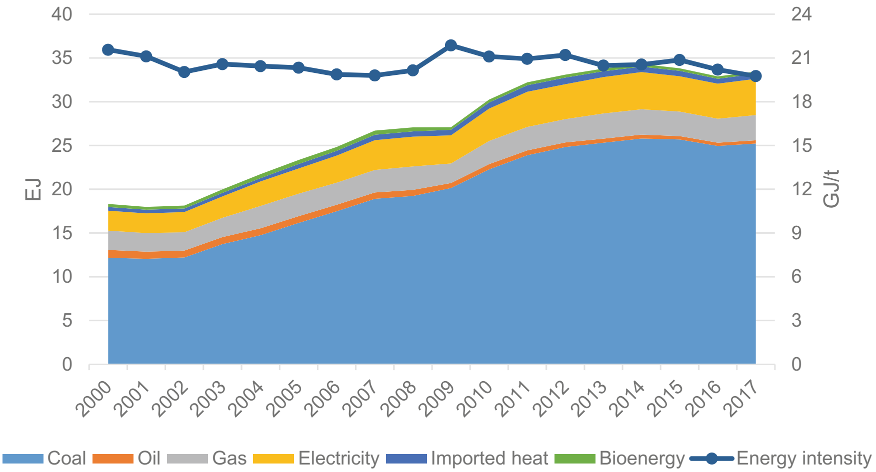

Fig. 7.6 Energy demand and intensity in iron and steel. *Source* IEA, energy demand and intensity in iron and steel, 2000–2017, IEA, Paris https://www.iea.org/data-and-statistics/charts/energy-demand-and-intensity-in-iron-and-steel-2000-2017

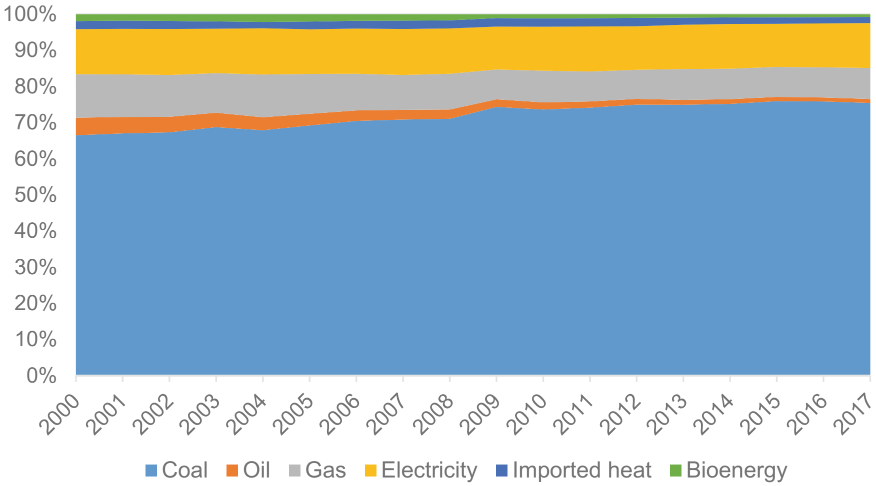

Fig. 7.7 Proportion of energy consumption in iron and steel. *Source* IEA, energy demand and intensity in iron and steel, 2000–2017, IEA, Paris https://www.iea.org/data-and-statistics/charts/energy-demand-and-intensity-in-iron-and-steel-2000-2017

a heavier blow on large and medium-size iron and steel plants; economic incentives launched by various countries sparked an explosive growth of iron and steel industry within a short period; meanwhile, unit energy consumption rebounded from 19.80 GJ/t in 2007 to 21.86 GJ/t in 2009, offsetting the previous efforts made by iron and steel industry, and it was not until later that a slow fall took place. The whole train of events in the beginning of 2020 heaped the risk of economic crisis, for which iron and steel industry should be adequately prepared to safeguard the achievements in energy conservation and emission reduction.

By energy consumption types, the composition of energy usage remains quite stable, with the proportion of coal increasing from 66.48% in 2000 to 75.41% in 2017 due to less application of petroleum, natural gas and biomass in iron and steel industry. Most of the coal is consumed in BF ironmaking, of which little room for energy consumption reduction is left (Wang et al. 2019). In fact, bigger share of coal is a positive effect of reduced consumption of other energy in iron and steel industry, implying that increasing the share of clean energy, finding substitutions for coal and improving coal efficiency are viable approaches for further progress in energy conservation and emission reduction in iron and steel industry.

The average energy consumption intensity of China's iron and steel industry in 2015 was 0.796tce/t crude steel (approximately 23.33 GJ/t), which breaks down into 0.575tce/ t crude steel (approximately 16.85 GJ/t) for leading steel plants −72% of the national average and 1.624 tce/t crude steel (approximately 47.59 GJ/t) for small and medium-sized steel plants, or 2 times of the national average. In 2015, China's benchmark steel enterprises for green development (national benchmark for short) were TISCO and Baosteel, with an energy consumption intensity of 0.547 tce/t crude steel (approximately 16.03 GJ/t) and 0.598 tce/t crude steel (approximately 17.53 GJ/t) respectively, i.e. 0.7 times and 0.8 times of national average. Large and medium-size iron and steel enterprises in China rank among the first echelon worldwide in term of comprehensive energy consumption, about 10% higher than the global average (20.86 GJ/t). The main cause is that small and medium steel mills in the industry featuring high energy consumption still produced about 20% of iron and steel in China, indicating the necessity to enhance the industrial concentration (Liu 2016).

In terms of CO_2 emissions, iron and steel industry worldwide contributes to approximately 5% of total CO_2 emissions from human activities; however, this proportion exceeds 12% in China (Hu 2016). With higher iron to steel ratio, small proportion of EAF, lower industry concentration and small capacity of unit facility, in 2010, CO_2 emissions from China's iron and steel industry accounted for 51% of the world's total CO_2 emissions; while this percentage was 12% for EU, 8% for Japan, 7% for Russia, 5% for US and 17% for the rest of the world (Xu 2010). These figures show that China's iron and steel industry emits far more CO_2 than other countries. In 2009, China produced 46.3% of the world's crude steel but caused 51% of global CO_2 emissions. A rough comparison would lead to the conclusion that China's emission intensity is far higher than other countries.

In terms of pollutant discharges, as indicated in Table 7.1, in 2015, pollutant discharges per unit of energy consumption of iron and steel industry were as follows: 5.59 kg/ton standard coal for dust and fume, 2.71 kg/ton standard coal for SO_2, 1.63 kg/ton standard coal for NO_x (referred to as national average); the dust (fume) emission and SO_2 emission by large and medium-size key iron and steel enterprises were respectively 0.3 time and 0.6 time of the national average; while for SMEs, these figures were respectively 2.0 times and 1.6 times, and for TISCO, a benchmark

Table 7.1 Pollutant discharges per ton of finished steel in iron and steel plants (kg/t finished steel)

Pollutant	Factor	Sintering	Coking	Ironmaking	Steelmaking	Steel rolling	Comprehensive	Total
Particles	Dust	3	1	2	0.5	0.6	–	7.1
	Smoke dust							
Fume	Sox	4	0.3	0.32	0.2	2	–	7
	Nox	1	0.2	0.2	0.1	0.5	–	2
	CO	40	0.3	5	15	0.33	–	60.63
	HF	0.04	Trace	Trace	0.01	Indefinite	–	0.05
	CxHr	0.1	0.2	0.05	0.05	0.2	–	0.6
Waste water	SS	0.28	0.06	0.24	0.07	0.2	–	0.85
	COD	0.05	0.08	0.16	0.2	0.14	–	0.63
	NH3	–	0.03	0.08	–	–	–	0.11
	Phenols	–	0.005	–	–	–	–	0.005
	Cyanides	–	0.02	0.03	–	–	–	0.05
	Chlorides	–	–	0.05	0.05	0.2	–	0.3
	Sulfates	0.004	–	0.003	–	0.4	–	0.407
Solid waste	Dust	Reuse	2	12	30	–	–	79
	Sludge			12	15	10	–	
	Residue	–	–	300	100	–	–	400
	Iron oxide scale	–	–	–	–	30	–	30

(continued)

Table 7.1 (continued)

Pollutant	Factor	Sintering	Coking	Ironmaking	Steelmaking	Steel rolling	Comprehensive	Total
	Oil-containing waste	–	–	–	–	10	–	10
Others	Refractory	–	–	–	–	–	20	20
	Industrial refuse	–	–	–	–	–	40	40
	Domestic refuse	–	–	–	–	–	10	10

Source He 2013

enterprise in China, these were respectively 0.1 time and 0.2 time while for Baosteel, respectively 0.1 time and 0.3 time of the national average. Emissions from sintering were the main contributor to emissions during production.

7.1.3.2 Forecast of Iron and Steel Consumption and Switch in Production Approach

Generally speaking, the average iron and steel stock per capita normally stays at a saturated level between 10 and 15 t in developed economies (which is one of the reasons for less fluctuations in the proportion of short process steelmaking in major developed countries). Despite the rapid growth in iron and steel stock per capita in China, it still falls short of this benchmark with an estimated 8t per capita in 2019. Therefore, China's demand for iron and steel is expected to grow with prospering economy and improved consumption; however, Chinese researchers generally believe that iron and steel consumption will not peak by 2020, as estimated by World Steel Association, but after that.

According to the forecast by Energy Transformation Commission (ETC), average annual consumption of iron and steel in China is expected to fall to around 475 Mt by 2050, which is consistent with the 2 °C scenario in IEA report. Besides, this research also predicts that steel in the future would increasingly derive from short process production using recycled scrap. With an increasing number of buildings, automobiles and other equipment approaching the end of their service life, the supply of scrap is expected to grow at a pace of 10% annually with significant drop in prices. The same study indicates that by 2050, 60% of total steel output in China would be from short process steelmaking. To attain this goal, policy support is needed to ensure maximum recycle and reuse of high-quality iron and steel. As implied by the forecast, the annual output of crude steel in China may decline from the current 760–190 Mt by 2050. Considering the direct export or use of iron and steel in exported commodities, China's total output of iron and steel will hit 700 Mt by 2050 in the high demand scenario, of which 280 Mt are from long process steelmaking (ETC 2019).

7.2 Low Carbon Technologies and Measures in Iron and Steel Industry

In recent years, profound changes have taken place in the outside environment of iron and steel industry in China and the world. Demands placed on iron and steel industry has become all the more challenging with depletion of high-quality resources for metallurgy, degradation of existing resources, price hikes in raw materials and fuels, mounting pressure of CO_2 emission reduction and environmental burden, plus the demand of INDC for energy efficiency and emission reduction. In this context, a new trend of resource efficiency and environmental friendliness has emerged in the technological development in iron and steel industry, which echoes the new round of technological revolution and industrial development. This trend is mainly manifested by efficient, green and circular manufacturing process, high performance, lower cost, better quality and easier processing of iron and steel materials, intelligence and customization of iron and steel manufacturing, etc. (Guo and Yang 2018). Efforts have been made on both the consumption and the production side by governments, research institutes and steel plants across the world.

7.2.1 Consumption Side

The key to reducing energy consumption and emission of iron and steel industry lies in enhancing the usage effectiveness of steel products, slowing down the demand growth, and increasing the efficiency and service life of the products. This can be achieved by the following means.

7.2.1.1 Saving Steel Through Improved Design

Building sector: the use of steel in commercial buildings in developed countries is twice of what is required by safety standards, which, however, has not resulted in longer service life, and the buildings would still be replaced within 30–60 years. This means if the building design is improved according to the safety standards while the life cycle is prolonged, it would be realistic to reduce the related steel demand and consumption by half or even more. For transport, the focus is on lightweight automobiles, i.e. producing and using more lightweight cars without compromising the service can cut the steel demand by heaps and bounds. Usually, in body design, finite element analysis (FEA) (Fig. 7.8) is employed for topological and structural optimization, reducing the quantity of steel used while ensuring the physical properties of components. In industry, iron and steel loss can be reduced by enhancing the service life and efficiency of the production lines and the industrial products related to iron and steel.

7.2.1.2 Material Substitution

Iron and steel can be partially replaced by cleaner materials. An example is using aluminum alloy and carbon fiber in the car industry. Taking the transport industry as an example, the Society of Automotive Engineers of China published the country's first *Technical Roadmap for Energy Conservation and New Energy Vehicles* in October 2016, painting the blueprint for China's car technologies for the forthcoming 15 years, in which lightweight vehicles were identified as a major part of energy conservation

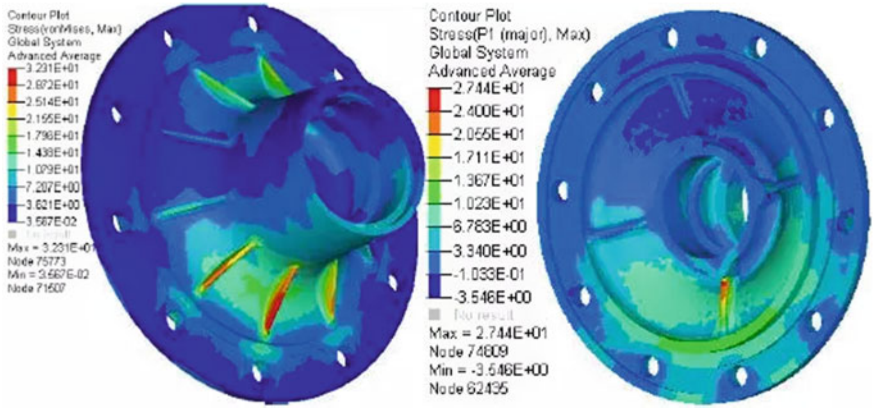

Fig. 7.8 Optimization of hub structure with hyperworks, a FEA software. *Source* https://youxy.gz7.hostadm.net/news/detail/id/187.html

and new energy vehicles. The Roadmap clearly stated the mid- and long-term development plan and development goals by 2020, 2025 and 2030 of lightweight vehicles. As shown in Table 7.2, the main approach is material substitution.

Table 7.2 Technological development roadmap of light materials for automobiles in China

Year	2020	2025	2030
Curb weight	10% reduction compared to 2015	20% reduction compared to 2015	35% reduction compared to 2015
High strength steel	Application of AHSS over 600 MPa) reaches 50%	Application of 3rd generation automotive steel reaches 30% of the weight of body-in-white	Certain percentage of application of steel over 2000 MPa
Aluminum alloy	190 kg of aluminum per vehicle	Over 250 kg of aluminum per vehicle	Over 350 kg of aluminum per vehicle
Magnesium alloy	15 kg of magnesium alloy per vehicle	25 kg of magnesium alloy per vehicle	45 kg of magnesium alloy per vehicle
Carbon fiber enhanced composite material	A certain quantity of carbon fibers used, with cost reduction by 50% compared to 2015	Use of carbon fibers accounting for 2% of vehicle body weight with cost reduction by 50% compared to the previous stage	Use of carbon fibers accounting for 5% of vehicle body weight with cost reduction by 50% compared to the previous stage

Source Society of automotive engineers of China 2016

7.2.1.3 Recycling and Reuse of Steel

A well-structured recovery, recycling and reuse system of iron and steel shall be put in place with more support granted for the recycling industry and for technological development in steel scrap, such as short process steelmaking.

7.2.2 Production Side—Higher Energy Efficiency from Technical Improvement

There are two approaches to enhance the overall energy efficiency of iron and steel industry: the first, R&D of energy-saving and emission reduction technologies on the technical level; the second, organizational improvement in iron and steel production on the management level.

7.2.2.1 Technical Level

Major approaches on the technical level are listed in Table 7.3, which are employed in different technical procedures to optimize the long and short processes: (1) enhance the gas circulation, product and waste flows; (2) improve charging of materials, such as injection of pulverized coal; (3) optimize the furnace design and process control; (4) recover more energy through adopting coke drying quenching, top gas recovery turbine, thin strip continuous casting; (5) recovery and reuse of residual gas/heat in each process. In fact, the expanding market has aroused the awareness of technological development for iron and steel industry, in which several rounds of technological upgrade have taken place. For the past 30 years since 1980, especially during the 1980s and 1990s, a series of key technological upgrade have occurred, such as BOF substituting open hearth furnace, continuous casting substituting ingot casting, one-time heating substituting multiple-time heating during rolling, etc., with notable progress. A cost/benefit analysis and identification of priorities are needed for these new technological options for the future low-carbon development of iron and steel industry.

7.2.2.2 Management Level

On the management level, managerial science is applied in organizing resource allocation and iron and steel production to cope with the challenges of low concentration, insufficient specialization, high cost and subsequently excessive production capacity in the industry as described in 7.1.1. This cannot be achieved without the hardware and software support in "power system" in the table above. In recent years, with the Industry 4.0 Strategy as stated in *Made in China 2025*, i.e. IT-empowered

Table 7.3 Energy saving and emission reduction technologies in iron and steel industry with higher energy efficiency and technical improvement at the core typical energy-saving and emission-reduction technologies in iron and steel industry

Procedure	Technique	Underlying method (in Part)
Row materials preparation	Environmentally-friendly enclosed stockyard of raw materials	
	Raw material blending technology	
	Variable frequency motor system technology for conveyor belt	
Coking	Moisture adjustment of coal	Removal of some moisture from coking coal before loading into chamber
	Pipe-type sensible heat recovery boiler technology	
	Cooling by residual hot water from the upper section of initial cooler	
	Negative pressure benzene removal	
	Residual heat recovery from waste gas of coke oven riser pipe	
	Coke dry quenching technology	Heat exchange with red coke using cold inert gas or waste gas from combustion
	SCOPE21 coking technology	
	Coal blending with waste plastics or rubber	
	Coke oven heating optimization control system technology	
	Ammonia distillation with tube furnace	
Sintering	Mini pellet sintering technique	
	Air leakage reduction in sintering	
	Low temperature sintering technique	
	High bed height sintering technology	
	Recovery and reuse of waste heat from circular sinter cooler	Introduction of hot waste gas into the furnace to produce steam for power generation

(continued)

Table 7.3 (continued)

Procedure	Technique	Underlying method (in Part)
	Reuse of interring fumes	
	Water seal circular cooler technology	Dual-phase gas–liquid dynamic balance sealing technology, thermodynamic simulation optimization
	New type vertical pot for sinter cooling and power generation from residual heat	Introduction of hot waste gas into the furnace to produce steam for power generation
	Large size straight grate palletizing technology	
	Circular sinter cooler and power generation from waste heat	Introduction of hot waste gas into the furnace to produce steam for power generation
	Waste heat recovery from large flue of sintering machine	
	High-pressure variable frequency adjustment of main exhausting system of sintering machine	
	Intensive mixing and palletizing technology for sintering	
	High frequency power source modification technology for dedusting fan of sintering machine	
	Blast furnace gas plus air pre-heating technology for sintering ignition	
	SHRT technology	
	Sintering with oxygen-rich air	
Palletizing	Grate-kiln palletizing technology	Preheating green pellet by waste heat from off-gas of kiln and circular cooler
	Reuse of waste heat from evaporation cooling system	
	Production technology of MgO-containing pellet or flux pellet	
	Recycle and reuse of waste heat from pelletizing	Recycle of waste heat from pelletizing

(continued)

Table 7.3 (continued)

Procedure	Technique	Underlying method (in Part)
Iron making	Quality raw materials preparation technology	
	Efficient pulverized coal injection technology of blast furnace	
	Granular coal injection technology of blast furnace	
	Power generation by dry top gas pressure turbine (TRT)	Top gas pressure recovery turbine, power generation with waste pressure and waste heat from top gas
	Blast furnace power recovery turbine technology (BFRT)	Blast furnace power recovery turbine, power generation with waste pressure and waste heat from furnace top
	High radiation prevention coating technology for hot stove regenerator	
	BF top gas circulation technology	Recovery and reuse of BF gas
	BF waste plastics injection technology	
	BF gas dry dedusting technology	
	BF dehumidified blast	Cooling and DE humifying the moisture of blowing air before hot stove
	Purification of BF gas by pressure swing absorption	
	Recovery and reuse of waste heat from BF slag and reuse of ultra-fines slag	
	BF top iso-pressure blow off optimization	Application of multiple devices such as rotary top-burning hot stove burner, orifice high-efficiency check bricks, grates of various hole types, etc
	Pre-heating and injection of pulverized coal into BF	
	BF coal injection lance technology	Direct injection of pulverized coal into BF

(continued)

Table 7.3 (continued)

Procedure	Technique	Underlying method (in Part)
	Plate type heat exchanger modification for hot stove	
	Anti-surge control optimization for fans	
	Dual pre-heating (air and gas) for hot stove	
	BF gas pneumatic blast technology	
Steel smelting	BOF fume dry dedusting technology	
	BOF "negative energy steelmaking" technology	
	Recovery of waste heat from BOF off gas	Recovery of gas and waste heat from BOF steelmaking
	Steam supply from BOF evaporation cooling system to vacuum refining furnace	
	Steel waster vacuum circular degassing dry (mechanical) vacuum system application	
	Optimized EAF power supply technology	
	fume dedusting/waste heat recovery and reuse technology	
	Polymer rubber injection technology	
	Waste heat recovery from self-disintegrating of slag	
	Regenerative ladle reheating technology	
	High-efficiency continuous casting technology	Liquid steel passes through water-cooling crystallizer, hardens and forms shell and then is drawn out, and then cut into billet after cooling and solidification
	Thin slab continuous casting technology	
Steel rolling	Low temperature rolling	

(continued)

Table 7.3 (continued)

Procedure	Technique	Underlying method (in Part)
	Online preheating treatment	System optimization and integrated control of processing and conversion
	Regenerative combustion technology	Installation of two regenerative burners for alternate heat storage and discharge
	Steel rolling preheating furnace evaporation cooling technology	
	Energy-saving technology of intensified radiation of reheating furnace black body	Expand furnace area, increase emissivity and irradiation
	Preheating furnace oxygen-enriched combustion burning technology	
	Cold rolling continuous annealing furnace steel strip temperature mathematical modeling	Integrating five procedures including cleansing, inspection, sorting, etc. into one procedure, hence significantly improving the thermal efficiency of annealing
	Recovery and reuse of waste heat from rolling reheating furnace fume	Recovery and reuse of waste heat from hot rolling/cold rolling
	Endless and semi-endless continuous rolling technology for steel strip production	
	Lubrication technology for rolling	
	CC-HCR technology	
	Energy-saving technology of bar slitting, control rolling and control cooling	Reduce the waiting time for reheating furnace and times of rolling, enhance rolling efficiency, achieve optimal control
	Recovery and reuse of hydrogen discharged from cover-type annealing furnace	
	Square billet non-heating rolling technology	
Power system	Pump rectification and energy-saving technology	

(continued)

Table 7.3 (continued)

Procedure	Technique	Underlying method (in Part)
	Energy-saving technology for compressor control system	
	Power generation from low-temperature waste heat	
	Energy-saving technology for air compressor management and control system	
	Recovery of waste heat from air compressor	
	Intensified heat exchange of steam condenser of gas generator unit	
	Ultra-high-pressure gas turbine-steam turbine power generation technology	
	Gas-steam joint circulation power generation technology	Power generation by gas turbine driven by combustion and expansion of BF gas and steam turbine driven by steam
	Gas turbine pilot fuel substitution technology	
	Bolt expansion energy-saving driving technology	
	High-voltage variable frequency speed regulation technology	
	Energy-saving and efficiency-boost control technology for electric precipitator	
	Reactive power compensation on the spot	
	Switched reluctance motor technology	
	Cast copper rotor motor technology	
	Hydraulic turbine driving technique for industrial cooling tower fan	
	Permanent magnetic speed-adjustable motor	

(continued)

Table 7.3 (continued)

Procedure	Technique	Underlying method (in Part)
	Power demand side management platform	
	Power grid boost	
	Power management center and optimization	
	Rooftop PV power generation	

Source Ma 2015; Li et al. 2017

industrial transformation, an intelligent steelmaking industry has become a crucial technological option for higher efficiency enabled by management. The application of intelligent approaches makes efficient, continuous and stable production possible while reducing the resources and energy use as well as CO_2 emissions in the production process. BOF (focusing on blowing endpoint control technology, such as static control model, auxiliary lance dynamic control technology, furnace gas analysis and control system, slag stopping and slag testing, sonar slagging technology, etc.), EAF (automatic loading of scrap steel, smart power supply, digital electrode control technology, automatic identification of slag clearance, foaming slag monitoring, temperature measuring and sampling, non-contact continuous temperature measurement and continuous fume analysis, multifunctional furnace door robot, real-time furnace monitoring including automatic steel tapping), continuous casting (quality control and efficiency enhancement, including multifunctional casting platform robot, ladle slag detection, automatic tundish casting, automatic control of crystallizer liquid surface, online width adjustment of crystallizer, hydraulic pressure vibration of crystallizer, electromagnetic smelting, automatic remote roller's gap adjustment of fan-shaped segment, dynamic soft pressuring, automatic water distribution for secondary cooling, energy-efficient flame-out billet cutting, size/weight specific billet cutting, automatic cleaning of billet surface, etc.), workshop operation (tracking management of lables, molten iron temperature control/distribution, smart casting crane, etc.), among other iron and steel industrial processes, are now given multiple technical options with the progress in testing and control hardware and AI algorithm software. Leading steel plants such as Baosteel have made tremendous headway in this respect (see Fig. 7.9) (Li 2019).

Energy conservation management in China's iron and steel industry started with energy consumption measurement, statistical study and establishment of the energy use indicator system. For the production procedures concerning energy conservation management, 17 "energy conservation rules during production" were devised in succession since 1979, accompanied by a rating and upgrading system which helped save energy during production and within companies. With the creation and improvement of energy management centers, energy management has also been put to use in iron and steel industry (Forward (Qianzhan) Intelligence Co. 2016).

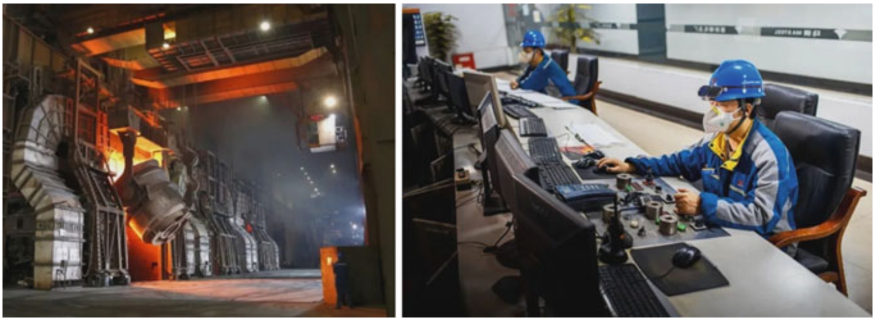

Fig. 7.9 Fully automatic steelmaking system of baosteel. *Source* https://www.sohu.com/a/308178089_99913579

Simply put, China's iron and steel industry has undergone a shift from experience-based management to modernized management, and energy-saving management also migrated from the responsibility of a single department to corporate-wide comprehensive management. But on the whole, the current energy management centers of individual enterprises are mostly loading energy use data and equipment operation information onto the digital platform and monitoring procedures with simple functions such as energy management statement, energy use analysis and HMI, while online task handling and optimization is not yet a reality, neither is the indicator system adequate for intensive management, hence much room for improvement. Underperformance has also prevailed in the management of the entire iron and steel industry, as evidenced by extra energy use and GHG emissions from chronic excessive capacity and inventory, a problem that should not to be ignored.

It is imperative to better manage the iron and steel industry. Individual enterprises are advised to deploy smart energy systems with continuous improvement of software platform and data mining platform; production optimization through R&D and smart energy systems should be put in place with intelligent technologies applied in production organization. The industry should firstly phase out obsolete capacity, optimize industrial structure and maintain balance between supply and demand, and secondly create an industry-wise data exchange platform with dynamic structural optimization, and build an expert advisory panel.

7.2.3 Production Side—Reduction in Carbon Input and Output

Another approach for low carbon development of iron and steel industry is to curb carbon input and output in various phases of production.

7.2.3.1 Reduction in Carbon Input

(1) Use cleaner fuel with better low-carbon performance during production process, such as clean power. (2) Upgrade production techniques to enhance energy efficiency, as elaborated in the previous section. (3) Replace coke and coal—traditionally important for iron and steel production with high-carbon emissions. In some places, gas-based direct reduction and oil–gas injection technologies have already in use, but only in smaller scale by far. Charcoal as another substitute for coke is currently used in iron and steel production, and its performance improvement provides an alternative for development. Other alternatives include using ferro-coke as reducing agent, using biomass and waste plastics to replace coal, and using hydrogen as reducing agent, etc. (Zhang et al. 2018).

7.2.3.2 Reduction in Carbon Output

CCS (carbon capture and storage) technology is deployed for centralized treatment of CO_2 to avoid extra greenhouse effect. CO_2 generated from combustion of fossil fuels in energy sector and other industries is either separated and captured for reuse, or transported by pipeline into geological stratifications thousands of meters underground or by vessels to the seabed for encapsulated storage isolated from atmosphere. Main capture methods currently in use are pre-combustion capture, oxygen-enriched combustion and post-combustion capture, the last being commonly adopted in iron and steel industry, which mostly employs technologies such as cryogenic separation, physical absorption, chemical absorption, membrane separation, etc. Major fields of application for captured CO_2 include oil displacement, CO_2 strengthened coal bed gas and food grade CO_2 refinement. This technology is recognized as effective in combatting climate change and cut carbon emissions. US, Australia, EU and the Middle East attach great importance to the development of CCS technology, providing policy and financial incentives and promoting scientific research to jointly address the climate issue.

Currently, CCS is the only available technology to dramatically (by as much as 90%) reduce CO_2 emissions from the power sector and the industries. Without CCS, the overall cost to reach the long-term goal of climate change mitigation at the national level would increase by 25%, i.e. 1 trillion USD (ETC 2019). Early demo projects of CCS in China make it possible to effectively and promptly promote this technology in the country in the next 10 to 15 years.

7.2.4 Production Side—Low Carbon Demo Projects

Ultra-low CO_2 iron and steel production demo projects have been launched across the world, centering on four new steelmaking technologies: top gas circulation for BF, smelting reduction technology, advanced direction reduction technology (mainly with hydrogen) and electrolysis technology, which, combined with new techniques of various procedures elaborated above (such as dry quenching, CCS, etc.), have aided multiple comprehensive low-carbon steelmaking projects with satisfactory results.

7.2.4.1 EU

To combat climate change, EU launched the ultra-low CO_2 emission steelmaking project (ULCOS) in 2004, aiming at reducing CO_2 emissions of iron and steel industry by around 50%. Upon research, demo projects based on four key technologies were later unveiled, namely TGR-BF (top gas recycle-blast furnace), ULCORED (new direct reduction technique), HIsarna (new smelting reduction technique) and ULCOWIN/ULCOLYSIS (alkaline electrolysis reduced iron).

TGR-BF: an iron-making technique using oxygen blowing and reusing top gas back in furnace after removing CO_2 via VPSA (vacuum pressure swing absorption) technology, its technical process illustrated in Fig. 7.10. This technology has three major features: first, replacing pre-heated air with pure oxygen, removing nitrogen and helping CO_2 capture and storage; second, using VPSA and CCS technologies to separate CO_2 and store it underground; third, recovering CO as reducing agent, thus less coke is used. In 2007, a test run of recycled gas injection into furnace hearth and body lasting 7 weeks was conducted by ULCOS project group in the experimental blast furnace (EBF) of LKAB Sweden in 2007. Results showed that when coal injection is 170 kg/t, coke ratio is reduced from 400–405 kg/t to 260–265 kg/t, carbon consumption cut by 24%; VPSA operation was smooth with 97% of BF top gas recycled, and 88% of CO recovered. Volume fraction of CO_2 was approximately 2.67%. When TGR is used in conjunction with VPSA and CCS technologies, CO_2

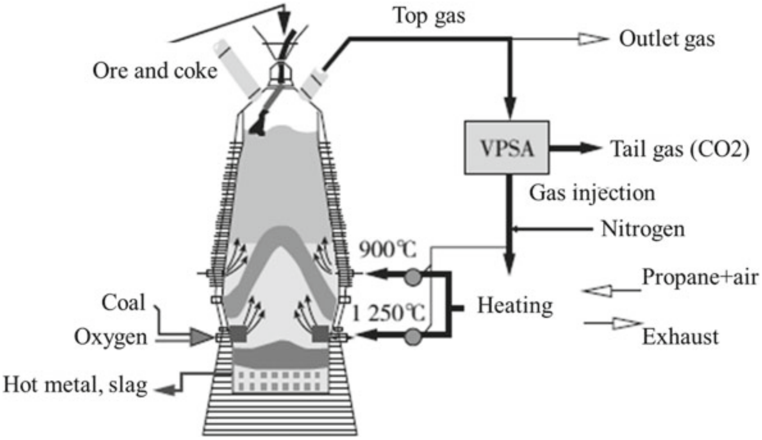

Fig. 7.10 Technical process of TGR. *Source* Zhang et al. 2018

emissions per ton of iron can be reduced by a maximum of 1270 kg, or 76% of total CO_2 emission from this procedure.

ULCORED (Sweden), HYBRIT (Germany), SALCOS (Austria) H2FUTURE: DRI by ULCORED technique uses reducing gases such as hydrogen generated from natural gas to reduce lump ores or pellets directly to sponge iron as raw materials for EAF steelmaking. The technical flow is as follows: loading sintered ores and pellets into DRI vessel from the top; reducing gas generated from natural gas is directly injected into DRI vessel for reduction reaction with iron ores to produce sponge iron. For ULCORED project, conventional reducing agent coke is replaced by reducing gas generated from natural gas, whose consumption is further reduced by vessel top gas recycling and pre-heating. This technology, in conjunction with CCS, can maximize CO_2 emission reduction while minimizing energy consumption, cutting CO_2 emissions of BF routine by around 70%. HYBRIT was jointly kicked off by Vattenfall, an energy supplier, SSAB and LKAB in April 2016, aiming at developing breakthrough ironmaking technology using hydrogen to replace coal and coke. According to project timeline, a feasibility study will be rolled out from 2018 to 2024, with a pilot plant built for experiments and a demo plant established between 2025 and 2035. This technology uses hydrogen as main reducing agent, which reacts with pellets and produces directly reduced iron (DRI) and water, where DRI is used as feed for EAF steelmaking. This technology curbs CO_2 emissions as the reducing agent—hydrogen mainly comes from electrolysis of water using clean power such as hydropower or wind power. Initiated by Salzgitter AG, SALCOS Project aims at gradual renovation of the legacy BF-BOF steelmaking technical process, replacing the carbon-intensive steelmaking technique based on BF with DRI-EAF technology, together with multi-purpose use of surplus hydrogen. To achieve this goal, Salzgitter AG plans to produce hydrogen by high temperature electrolysis using wind power or power generated by waste heat from steel plants.

HIsarna: the process flowsheet of HIsarna is illustrated in Fig. 7.11. Iron ore is loaded from the top of reactor, smelted in high-temperature cyclone smelting furnace and drips down to the bottom of reactor. Pulverized coal injected into reactor reacts with smelted ore, generating hot metal and CO_2. The process flow consists of three procedures: pre-heating and pyrolysis of coal, smelting and pre-reduction of iron ore and molten iron finally reduced in furnace bottom bath. Compared to conventional BF workflow, Hisarna uses much less coal as it gets rid of sintering and coking, both featuring high energy consumption and pollution. Combined with CCS technology, 80% of CO_2 emissions can be reduced. In September 2010, TATA Steel Ijmuiden launched Hisarna pilot plant, where 4 experiments have been carried out up to now. If industrial application becomes successful, this technology will contribute to less energy consumptions and CO_2 emissions, lower production costs and significantly enhance resources efficiency.

ULCOWIN/ULCOLYSIS: this technique uses electricity to decompose iron ores into iron and oxygen. Electrolysis in ironmaking generates zero emission. By far, the most promising technical options of iron ore electrolysis are electrolysis metallurgy (ULCOWIN) and direct reduction by current (ULCOLYSIS), both of which are still in experimental phase. In small-scale pilot tests, the purity of iron

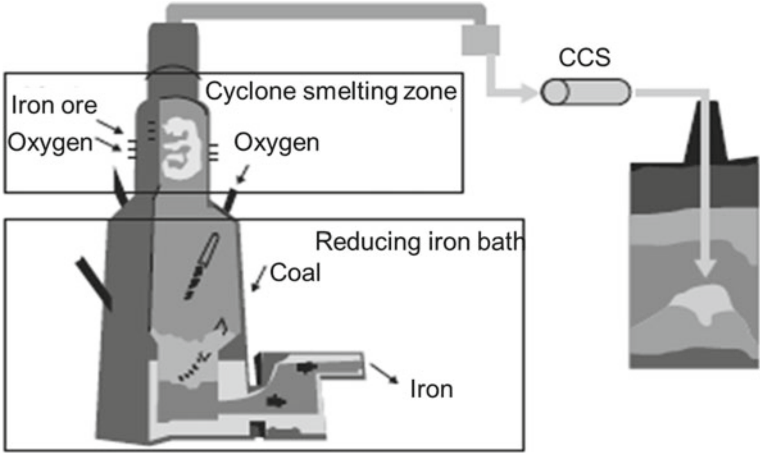

Fig. 7.11 Hisarna technical process of smelting reduction. *Source* Yan 2017

produced by ULCOWIN technique can hit 99.98% with energy consumption of 2600–3000 kW·h/t. However, the daily production capacity is merely 5 kg in the pilot plant. Later, ULCOS project team developed ULCOLYSIS technique, where iron ore is smelted in the bath at a temperature of 1600°C and electrochemical reaction occurs (Yan 2017).

7.2.4.2 Japan

COURSE50 Project conducted by Japan Iron and Steel Federation fuses hydrogen DRI and BF gas CCS technologies, adopting a new technique of hydrogen separation from coke gas and amine purification of BF gas, cutting approximately 30% of CO_2 emitted from production workflow. When developing BF CO_2 emission reduction technologies, Japan Iron and Steel Federation has built a test BF with 12 m^3 of inner volume, defining the reaction control technology that maximizes the hydrogen reduction effect while improving CCS. The project is scheduled to start trial-run in 2030, and to be disseminated and widely used by 2050 in combination with BF equipment upgrade.

7.2.4.3 U.S.

Low carbon steelmaking research in US seeks to develop new technologies to slash CO_2 emissions in iron and steel production, among which two new low-carbon technologies prove to be most effective: one is high-temperature electrolysis of molten oxide based on the mechanism shown in Fig. 7.12, where liquid FeO is decomposed into molten iron and oxygen by electrolysis without producing CO_2; second is the

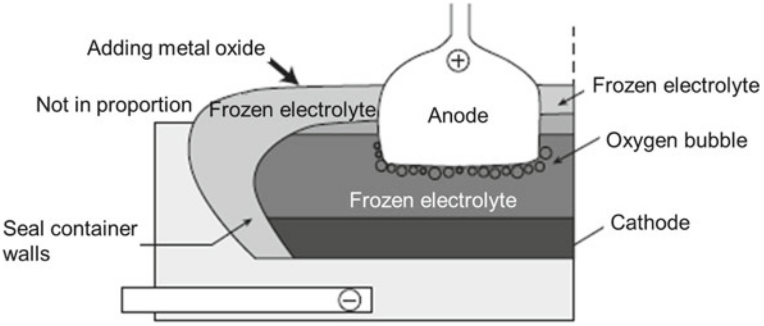

Fig. 7.12 Workflow of ironmaking by high-temperature electrolysis of molten oxide. *Source* Zhang et al. 2018

application of hydrogen reduction of iron in flash furnace reactor, cutting CO_2 emissions by eliminating coal and coke used in ironmaking, a technology developed by University of Utah and is still in the laboratory phase (Zhang et al. 2018).

7.2.4.4 China

Many trials have been conducted in new steelmaking technologies in China, among which two direct reduction technologies, namely nuclear hydrogen generation-hydrogen steelmaking and COG/syngas steelmaking are especially impressive.

Nuclear hydrogen production—hydrogen steelmaking: a dynamic momentum is unfolding in nuclear power development in China, where the importance of nuclear hydrogen production technology is well-acknowledged and a great many nuclear power plants are being built. High-temperature gas-cooled reactor provides heat for high-temperature processes and is the most suitable reactor for hydrogen generation. With the support of National 863 Plan, INET of Tsinghua University has been engaged in nuclear power development as illustrated in Fig. 7.13. 10 MW experimental high-temperature gas-cooled reactor (HRT-10) was built in 2001 and reached full capacity since 2003. Currently, the construction of 200 MW high-temperature gas-cooled reactor demo plant is recognized as a national key science and technology project while nuclear hydrogen generation is among special R&D projects. The ultimate goal of INET project is to make hydrogen generation by high-temperature gas-cooled reactor possible by 2020. Technical mechanisms selected are thermal chemistry I-S cycle and high-temperature steam electrolysis (HTSE). The technical research comprises four phases: (1) initiation of R&D and preliminary preparation (2005–2007); (2) hydrogen-generation technique validation (2008–2009); establishment of I-S cycle lab table (10L/h), experimental system for high-temperature electrolytic reactor hydrogen generation (1L/h) and uninterrupted operation of hydrogen generation system; (3) expanded lab test (2010–2014); creation of lab-scale I-S cycle

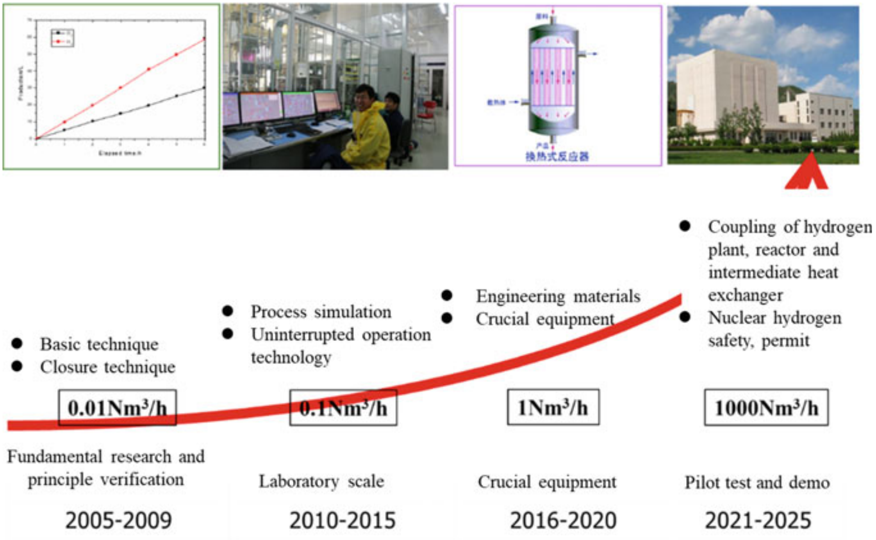

Fig. 7.13 Development journey and plan of nuclear hydrogen generation-hydrogen steelmaking in tsinghua university. *Source* Zhang Ping, chemical engineering and technology laboratory, INET, Tsinghua University

experimental system (60L/h) and HTSE experimental system (60L/h) and long-duration operation of these systems; (4) pilot production coupled with HTR-10 (2015–2020): the technique for pilot production will be selected based on operation of the 2nd phase and the progress in nuclear hydrogen worldwide. Currently the project is in its 3rd phase with research kicked off on crucial equipment and engineering materials and experiments expanded. In 2019, Baowu Group, CNNC and INET of Tsinghua University signed *Strategic Cooperation Framework Agreement on Nuclear Power-Hydrogen Generation-Metallurgy Coupled Technology*, agreeing to share their resources for joint construction of a world-leading nuclear metallurgy industrial alliance.

Coke oven gas/syngas steelmaking: gas-based DRI technology is another R&D focus of Chinese iron and steel enterprises in recent years. Deterred by the high cost of natural gas, these enterprises are keenly interested in DRI with gas obtained from COG or gasified coal to reduce the production cost of syngas or hydrogen. Prof. Zhou Hongjun's team from China University of Petroleum (Beijing) developed dry reforming and conversion technology of coke oven gas CO_2 and, in partnership with Sinopec and China Shanxi Taihang Mining Co., Ltd., built a demo plant of gas-based DRI using coke oven gas in Zuoquan, Shanxi, with an annual capacity of 300,000 tons (Fig. 7.14). The issue of the source of reducing gas in coke oven gas purification and dry reforming and conversion of CO_2 was resolved with new techniques developed by the university. This pilot plant is slated to be operational in 2020, which, together with existing projects such as the coal mine reorganization and expansion project of

Fig. 7.14 Demo project of coke oven gas DRI co-built by China university of petroleum, sinopec and China Shanxi Taihang mining in Zuoquan, Shanxi. *Source* Zhou Hongjun, China university of petroleum

900,000 t/year, coal washing reorganization and expansion of 2.1 million t/year, and coking facility of 1 million t/year, will form a complete industrial chain.

7.3 Technological Features and Application Prospects of Hydrogen Steelmaking

7.3.1 Technological Features

Hydrogen steelmaking boils down to substituting the reducing agent used to reduce iron ore to pig iron in conventional technique by hydrogen, thus replacing fossil fuels such as coke based on the principle of reaction between iron ore and hydrogen producing sponge iron and water. Hydrogen steelmaking will essentially eradicate CO_2 emissions, and is recognized as one of the best emission reduction technologies in iron and steel industry so far. Various demo projects have been conducted in different countries according to their resources endowment and technological strength, such as Austria, Sweden (HYBRIT), Germany (SALCOS) and Japan (COURSE50), all of which have been in progress for three to seven years, with some already under large-scale empirical research. The Chinese government and enterprises have also shown interest in hydrogen steelmaking. In 2019, Baowu Group entered into cooperation with CNNC and Tsinghua University in hydrogen steelmaking, and plans to partner with Rio Tinto in innovative low-carbon metallurgy.

Carbon reduction in hydrogen steelmaking depends on two factors: steel making and hydrogen generation, the former consisting of four key techniques:

- Hydrogen increase technique (water gas conversion): modification of coke oven gas (COG) to increase the hydrogen content to the level required by hydrogen reduction;

- Production techniques: development of new technologies required in actual production, such as hydrogen injection, furnace chemical reaction optimization, reduction of ores of low deductibility and low grade, design of coke/sinter/slag quality, etc.
- Development of ultra-thermal-resistant/ultra-corrosion-resistant materials: ultra-corrosion resistant materials used for high-temperature, high-pressure storage of hydrogen at over 900 °C need to be developed;
- Direct reduction of iron (DRI): direct reduction of iron ore at its solid state with hydrogen.

Apart from steelmaking technology itself, the source of hydrogen used in steelmaking also produces major impact on carbon reduction. Currently there are mainly two hydrogen sources in the demo projects:

- Gray hydrogen/blue hydrogen (hydrogen from natural gas/hydrogen as by-product of coking) + CCUS: such as COURSE50 project in Japan, its technology roadmap is illustrated in Fig. 7.15, where hydrogen separated from coke oven gas is used as reducing agent and the carbon reduction performance depends on the performance of CCUS technology:

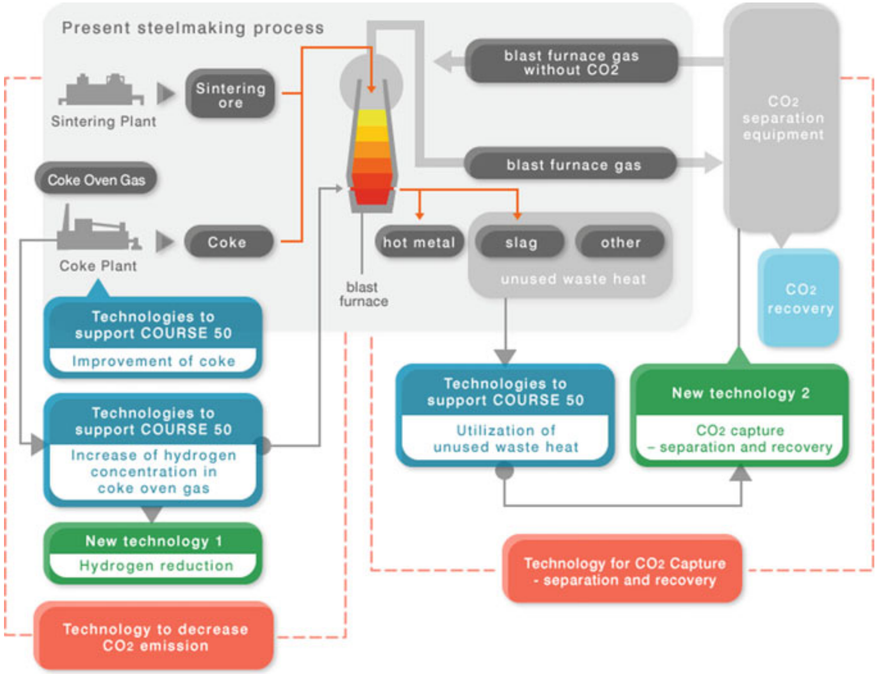

Fig. 7.15 Technology roadmap of course 50 in Japan. *Source* https://www.jisf.or.jp/course50/outline/index_en.html

- Green hydrogen (wind power/PV hydrogen generation, hydrogen generated from waste heat of steelmaking, nuclear power hydrogen generation): most demo projects show intention to eliminate CCUS and directly use green hydrogen for production, with its framework shown in Fig. 7.16. HYBRID project in Sweden, SALCOS project in Germany and H2FUTURE project in Austria are all jointly operated by local steel plants, power plants and electrolytic cell suppliers (such as Siemens and Sunfire), with a dedicated hydrogen supply sub-project (such as GrInHy2.0 under SALCOS project in Germany) to ensure facilities for wind/PV renewables and electrolytic cells. Among these, SALCOS project in Germany plans to use waste heat from iron and steel industry for power generation/heat supply for solid oxide fuel cells apart from wind power and PV. Baowu Group in China, in collaboration with CNNC and Tsinghua University for prospective study on adopting nuclear for steelmaking and hydrogen generation. The plan includes simultaneous hydrogen and power generation by I-S circulation deploying high temperature gas cooling reactor, where hydrogen is used for DRI and electricity for EAF steelmaking.

If hydrogen production is zero-carbon in itself, zero-carbon in iron production can be achieved by hydrogen-enabled DRI, be it water electrolysis or CCS application in methane steam reforming or coal chemical processing that is used for hydrogen generation.

7.3.2 *Potentials of Application*

Potentials of application for hydrogen steelmaking should be viewed from two perspectives: the overall expected emission reduction of each demo project which will be driven by policy, economics and technical capability, and emissions and abatement potentials of hydrogen generation for each project in its entire life cycle.

7.3.2.1 Project Level

About 120 GJ hydrogen is needed per ton of iron produced by DRI, from which the sponge iron can be used for EAF steelmaking. A development plan of 400Mt hydrogen DRI in East Asia has been mapped out by Gielen et al. (forthcoming). It is expected that iron and steel output of BF/BOF would be 525Mt by 2035 and 423 Mt by 2050. Given this forecast, the emission reduction potential would be approximately 50Mt in 2035 and 500Mt in 2050 (Gielen et al. forthcoming). Compared to BF/BOF, CO_2 emissions would be cut by 80–95% if DRI with hydrogen generation from renewables—EAF is adopted (Otto et al. 2017; Prammer 2018).

HYBRIT Project: the energy flow chart and the consequent emission reduction are illustrated in Fig. 7.17. CO_2 emissions per ton of steel produced by SSAB with long-process technique is 1600 kg (other European countries generally range between

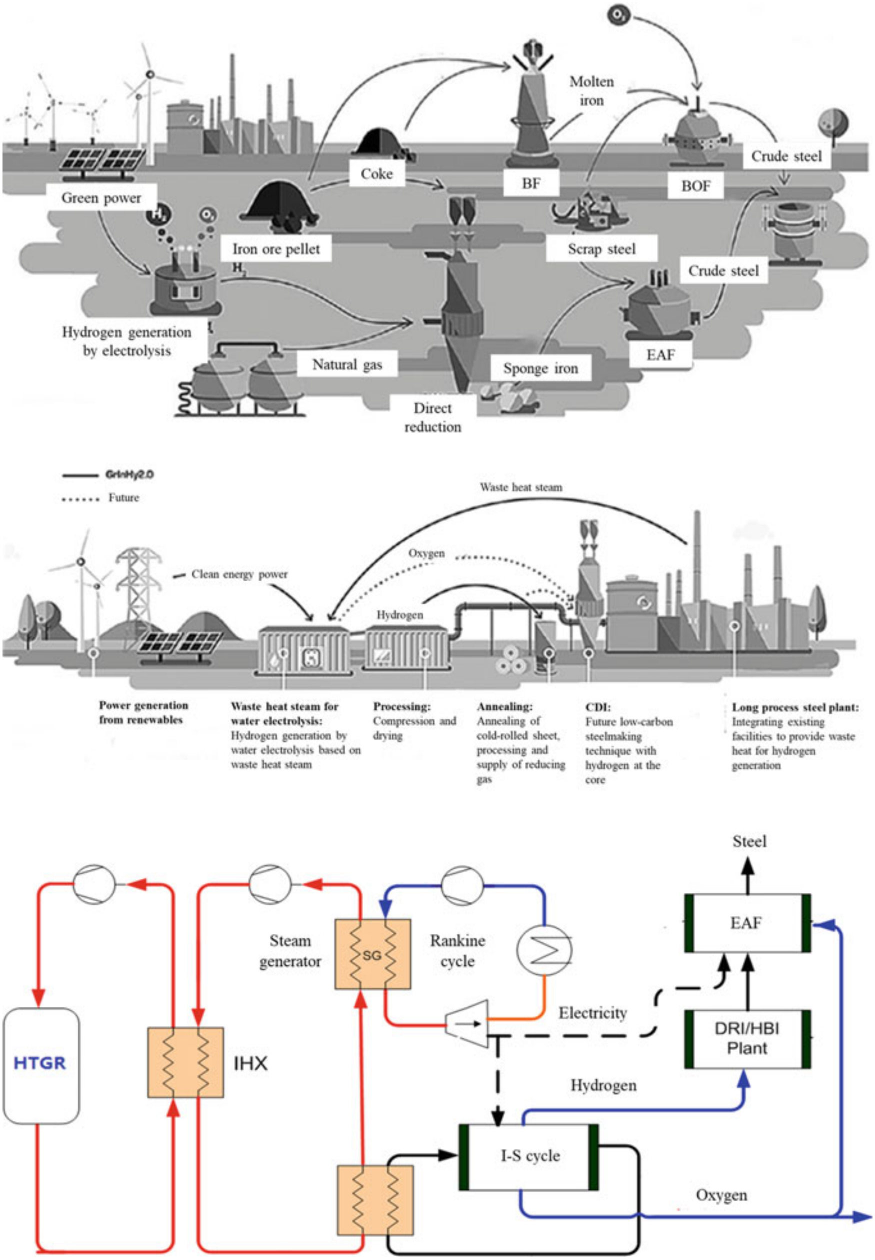

Fig. 7.16 Production structure diagram of green oxygen steelmaking projects worldwide (top down: SALCOS Project, H2FUTURE Project (GrInHy2.0Hydrogen Supply Sub-Project), INET nuclear steelmaking project). *Source* China steel news, https://www.csteelnews.com/xwzx/gjgt/201907/t20190719_13780.html Zhang Ping, chemical engineering and technology laboratory, research institute of nuclear and new energy technology, Tsinghua university

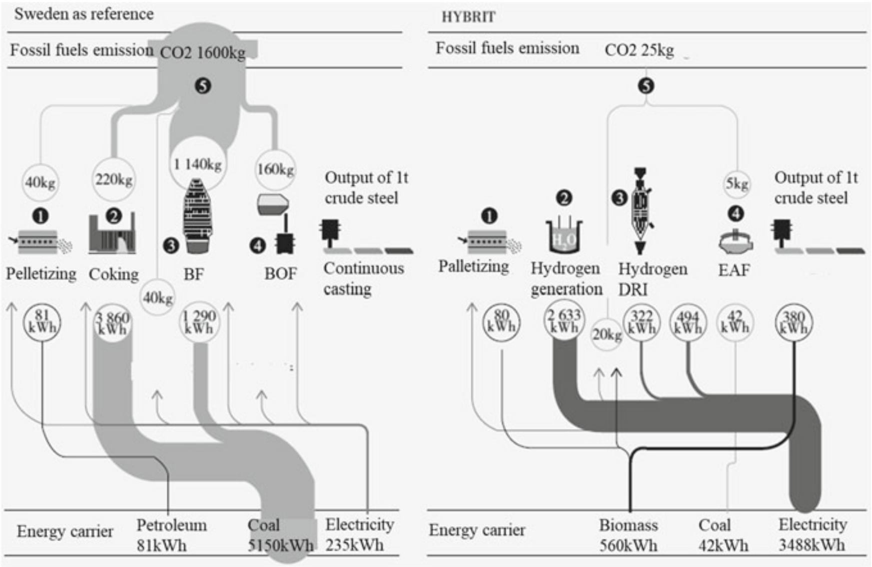

Fig. 7.17 Energy consumption and emission analysis of HYBRIT project in Sweden. *Source* https://www.worldmetals.com.cn/viscms/bianjituijianxinwen1277/20180906/245527.html

2000 and 2100 kg), and the total energy consumption is 5385 kWh equivalent. These two figures are respectively 25 kg and 4051 kWh for HYBRIT technique, i.e. cutting CO_2 emissions by 98% compared to BF technique (Yan 2017).

COURSE50 Project: the project aims at reducing carbon emission by 10% through hydrogen steelmaking and by 20% through CCUS. The first test run lasting around three weeks with a test BF was conducted in July 2016, with carbon input equivalent to CO_2 emissions and the result was compared to the operation conditions without hydrogen injection. It was confirmed that CO_2 emissions declined by 9.4%, close to the target of 10%, and the optimal operational condition for maximized hydrogen reducing effect was clarified, i.e. the blowing-in process injecting hydrogen into furnace is the key. A continuous running mechanism of injecting the furnace gas produced from test BF into the CO_2 separation and recovery test equipment was conducted as well.

H2FUTURE Project: the project seeks to combine hydrogen generation from renewables such as wind or PV with other engineering enhancements to attain the ultimate goal of slashing CO_2 emissions by 80% by 2050.

INET, Tsinghua University: general measurement and calculation was done on nuclear hydrogen generation for steelmaking. The estimated energy demand for a steelmaking facility of an annual capacity of 1 Mt breaks down as follows: total energy: $2.72*10^7$ GJ (870 MWh); heat: $1.7*10^7$ GJ (546 MWh); electricity: $4*10^6$ GJ (130 MWh). An HTR-PM600 can satisfy all energy demand, including hydrogen, electricity and heat for an annual capacity of 1.8 Mt of steel; in other words, 400

HTRs of 600,000 kw each are needed for 600 Mt of steel, the corresponding CO_2 emission is 1 kg/ton of steel, which is slightly lower than HYBRID project.

The results from the above theoretical research and demon projects show that actual production conditions and technical options vary with different regions. Generally speaking, the cleaner the hydrogen as fundamental, the greater potentials for carbon reduction, with the maximum percentage of over 80%.

7.3.2.2 Hydrogen Generation

As is stated above, the carbon reduction performance of hydrogen steelmaking depends on the source of hydrogen. A review of analysis results of GHG emission throughout the lifecycle of existing hydrogen power worldwide enables the estimation of GHG emission reduction potentials of different hydrogen sources, as illustrated in Fig. 7.18. The following conclusions can be drawn: results of different case studies are highly dispersed with high uncertainty of emission research results obtained from different technical options and national situations; it is basically clear that hydrogen production from renewables features good low-carbon potentials while steelmaking with hydrogen from grid power/fossil fuels have little advantage in GHG emission reduction compared to direct use of coal under the current conditions.

Apart from the aforementioned emission reduction potentials, the actual application potentials of hydrogen ironmaking are also subject to the following factors:

(1) Infrastructure cost, see 7.3.3;
(2) High energy consumption and carbon emissions in the storage and transport along the hydrogen supply chain, as hydrogen is of low density, difficult to compress and prone to leakage;
(3) Service life and safety of production materials and the consequent public awareness.

7.3.3 Carbon Reduction Cost

HYBRID Project: research results announced in the beginning of 2018 indicated that for a 240 MW hydrogen generation facility and BF with an initial investment of 30 million euros, the cost of hydrogen metallurgy technique adopted by HYBRIT project is 20–30% higher than traditional BF in Europe, calculated on the basis of power and coke prices and CO_2 emission trading price.

SALCOS Project: Salzgitter took the initiative in mapping out and implementing Wind H2 Project using wind power to produce hydrogen. The project deployed wind power for hydrogen generation through electrolysis, and applied hydrogen to the cold rolling process as reducing gas, and eventually injected the oxygen into BF. For the wind power part, 7 wind generators of a total capacity of 30 MW were built by a partner wind power supplier, 3 of which were located in a facility in Salzgitter. According to the project plan, the first step was to build a proton exchange membrane

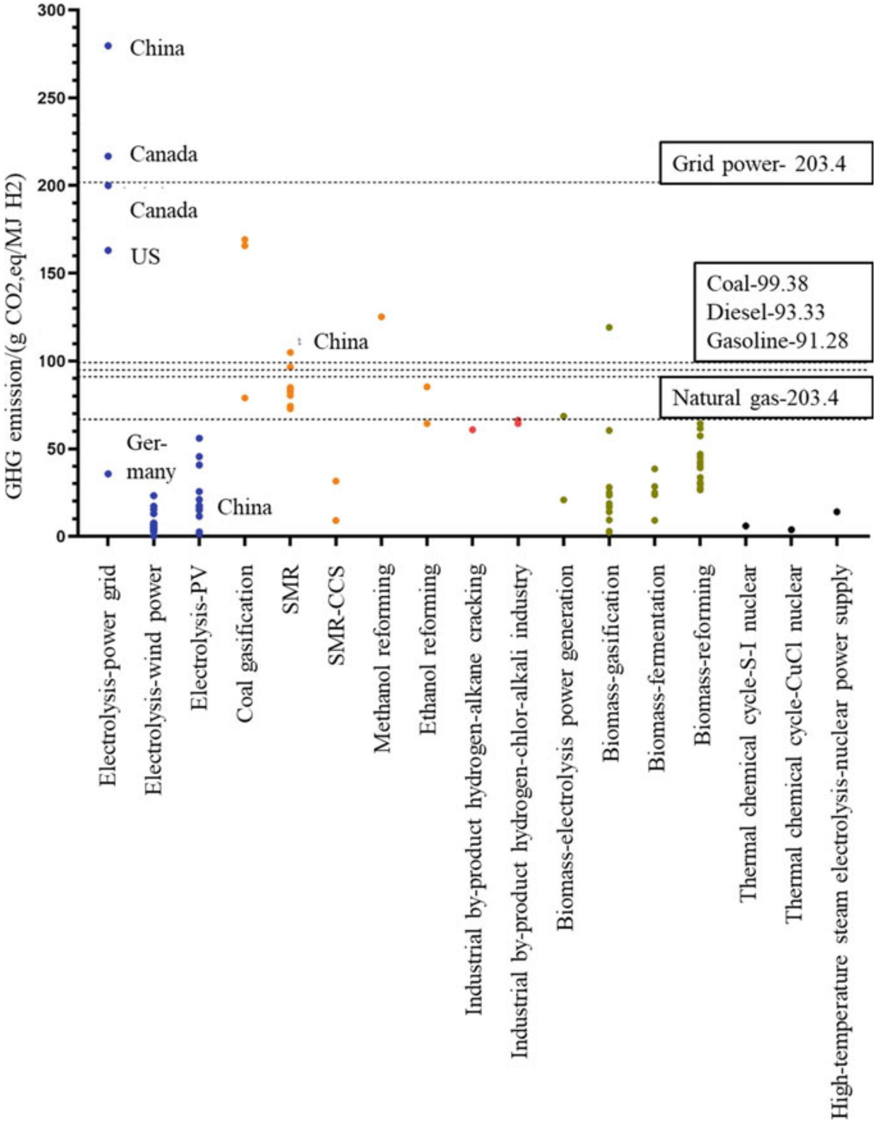

Fig. 7.18 Research results of GHG emissions of various hydrogen generational technologies throughout their life cycle. *Source* publications on hydrogen LCA case study worldwide

electrolyzation cell of a hydrogen generation capacity of 400 Nm^3/h, and the distilled water came from the water purification facility in the steel plant; the second step was power transmission from the wind power plant to the water electrolysis plant. The total investment in the wind power facilities and the hydrogen generation plant added up to around 50 million euros, and the latter is to be put into operation in 2020. On this basis, studies will be conducted on using other clean energy for power generation. In this project, Linde AG is responsible for hydrogen transport, mainly by gas tank vehicles (Source: https://steelguru.com/search/all/Salzgitter/result; https://www.wirechina.net/?thread-1498-112.html).

Estimation by INET/JAEA (Japan Atomic Energy Agency): Based on parameters of direct reducing projects of JAEA, researchers of INET estimated the cost of nuclear steelmaking, which, although not yet commercialized, can be calculated based on the price of direct reducing steelmaking (replace the price of natural gas supply and the investment of reformer with nuclear hydrogen, and reduce the cost of carbon sequestration). The result is a function of hydrogen price, which is then compared with conventional process. With the average price of steel throughout the 10 years from 2000 to 2010, i.e. 670 USD/t steel (coke and BF) and 675 USD/t steel (natural gas reducing) as a reference, the estimated nuclear hydrogen cost is 2.45 USD//kgH_2 and the corresponding nuclear steelmaking cost is 628 USD/t steel, suggesting competitiveness against conventional techniques.

On the whole, be it steelmaking with hydrogen generation from renewable energy or from nuclear, the total cost is much higher than conventional steelmaking due to the considerable cost of infrastructure (wind power/PV installations/electrolysis cell/high-temperature gas-cooled reactor, etc.) And the cost optimization shall depend on technological progress and carbon market development.

7.4 Technical Features and Application Prospects of CCUS Technology in Iron and Steel Industry

7.4.1 Technical Features

Prior to using clean hydrogen for DRI, CCUS almost stood as the only technical option for zero carbon emission of iron and steel industry. Meanwhile, as zero emission remained less of a priority for iron and steel industry in the past, and CCUS does not help to boost efficiency of iron and steel industry as it does for oil and gas, the momentum of CCUS has been lackluster compared to technologies aiming at improving the production efficiency. The technical options and their categorization of different phases of CCUS are illustrated in Fig. 7.19.

7.4.1.1 Capture

The main source of CO_2 emissions of iron and steel industry is the flue gas from combustion, and post-combustion of CO_2 from the flue gas is the least complicated

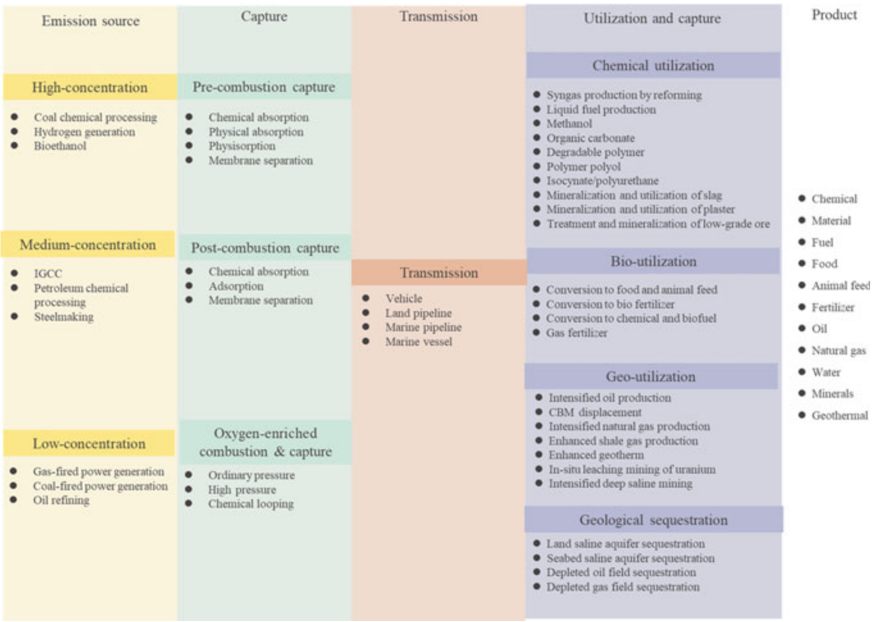

Fig. 7.19 Technical process and categorization of CCUS. *Source* Ministry of science and technology 2019

carbon capture technology in iron and steel industry. Currently used CO_2 separation technologies mainly include chemical absorption (absorption with acidity-alkalinity), physical absorption (temperature-varying or pressure-varying absorption) and membrane separation, the last being recognized as a promising technology with vast potentials in energy consumption and equipment compactness. Theoretically, post-combustion capture is applicable in both existing plants and plants under construction. The priority of CO_2 capture technology should be based on the possibility of avoiding CO_2 emissions and the level of difficulty of capture, the former depending on total CO_2 emissions while the latter on CO_2 concentration and existence of other pollutants in the flue gas. According to statistics (Seetharaman 2013; Wiley et al. 2011), CO_2 in BFG accounts for 35% of total emissions from iron and steel plants; therefore, pre-combustion capture of CO_2 is a feasible option. Pre-combustion capture is mainly used in IGCC system where coal is gasified under high-pressure, oxygen-enrichment conditions, and CO_2 and hydrogen are generated after water gas shift, where the gas pressure and CO_2 concentration are both high enough for CO_2 capture, and the residual hydrogen can be used as fuel. Pre-combustion capture is considered as one of the most promising carbon capture technologies as it effectively avoids the massive flow of flue gas and low CO_2 concentration after combustion in most coal-fired power plants. Currently available CO_2 separation technologies for pre-combustion capture include physical absorption (represented by Selexol method) and chemical absorption (represented by MDEA method). However, pre-combustion

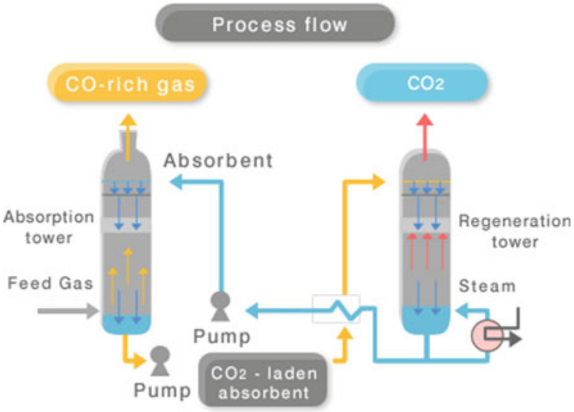

Fig. 7.20 Typical carbon capture process of iron and steel industry, with COURSE50 as an example. *Source* https://www.jisf.or.jp/course50/tecnology02/index_en.html

CO_2 capture from BFG may reduce the possibility of CO_2 capture from flue gas after combustion. Another approach is separating hydrogen from BFG, making the residual CO_2 easier to capture (Jiang et al. 2021).

COURSE50 in Japan is an example of the development of carbon capture technology in specific projects, as illustrated in Fig. 7.20. High-performance chemical absorbent is developed to enhance the efficiency of physical absorption, and taps into the unused heat during CO_2 desorption to further lower the cost. The chemical absorption technique is briefly described as follows: the liquid absorbent is in countercurrent contact with the feed gas in absorption tower and selectively absorbs $CO_{2.}$ When CO_2 concentration increases, the high-concentration liquid absorbent is pumped into the regeneration tower, heated to approximately 120 °C to release CO_2; the regenerated liquid absorbent is cooled and pumped back into the absorption tower. CO_2 separation and capture are achieved by repeated absorption and desorption.

7.4.1.2 Storage

For storage alone, the storage of CO_2 captured from iron and steel industry is similar with that from other industries, where main technical options include land saline aquifer sequestration, depleted oil and gas reservoir sequestration and seabed saline aquifer sequestration, as shown in Fig. 7.21. The option depends on the construction of storage space and corresponding comprehensive planning for iron and steel industry.

7.4.1.3 Utilization

Direct storage of captured CO_2 is a carbon reduction technology where a single move could affect the whole system as it involves multiple issues such as infrastructure, selection of place and method of storage and the consequent construction plan for

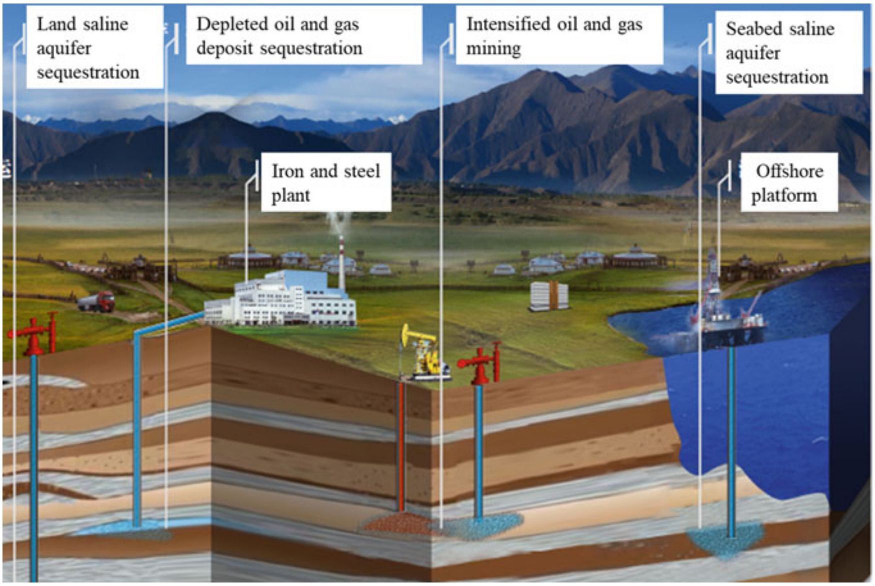

Fig. 7.21 Storage structure of CO_2 from iron and steel industry. *Source* Cai Bofeng et al.(2020)

iron and steel industry. As a comprehensive project, it only becomes realistic when technologies are mature enough and coordination between sectors becomes possible. Therefore, Chinese researchers have placed their focus on direct use of captured CO_2 in iron and steel industry, to which contributions are made by Zhu Rong's team from Beijing University of Science and Technology and Zhou Hongjun's team from China University of Petroleum:

CO_2 mixing gas: replacing nitrogen or argon in top/bottom blowing of BOF (see Fig. 7.22) and playing stirring liquid steel role in ladles. As CO_2 reacts with carbon to produce twice as much CO, such technique helps to remove undesired gases and inclusive, reduce iron loss in slag and increase dephosphorization rate. The disadvantage, however, is that the service life of equipment might be compromised as CO_2 is oxidizing.

CO_2 as reaction agent in steelmaking: CO_2-O_2 mixed injection steelmaking. CO_2 reacts with Fe/P/Si under high temperature, some of the reactions ranking higher than oxygen in the hierarchy. This helps to cut down the volatilization and oxidation loss caused by direct impact of oxygen on molten iron. Experiments conducted by Zhu Rong's team found that the fume and dust was reduced by 7.36–15.72%, limestone consumption by 1.8–3 kg, oxygen by 1 Nm^3 and calorific value of gas also increased for mixed injection steelmaking (Zhu et al. 2013).

CO_2 as protective gas in steelmaking: the physical and chemical properties of gasified CO_2 or dry ice enable them to partially replace the function of nitrogen as protective gas in steelmaking, which helps to bring down steel loss as well as nitrogen content and pores in finished steel products.

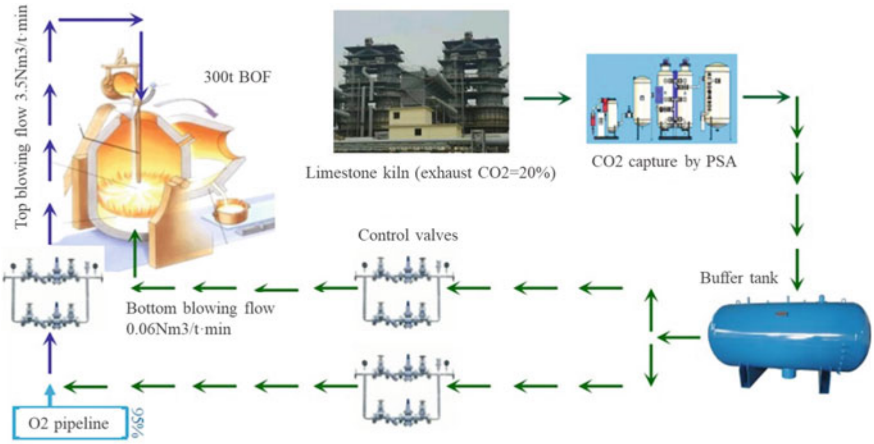

Fig. 7.22 Structural diagram of CO_2 top blowing/bottom blowing. *Source* Zhu Rong, Beijing university of science and technology

CO_2 as raw material for syngas: the drying reforming reaction of CO_2 and methane makes it possible to use COG to produce syngas CO and hydrogen, where the syngas can be used in DRI steelmaking or production of chemicals such as ethanol. Zhou Hongjun's team in China University of Petroleum conducted a study on this technology, which is currently in pilot production phase. The production flow is illustrated in Fig. 7.23.

7.4.2 Potentials for Application

7.4.2.1 Capture

Capture in a single project: the experimental COURSE50 project in Japan indicates that under the technical framework of hydrogen recovery from COG-steelmaking, CCS technology alone enables carbon emission reduction of around 20%; while in conventional BF/BOF steel plants, post-combustion CO_2 capture may cut approximately 40% of total CO_2 emission, and an extra 20% from the exhaust from main blower (Jiang et al. 2021). If the best available technologies (such as DRI etc.) are applied in the entire plant and expected outcome can be achieved for the ongoing technological R&D projects, by 2050, emissions from iron and steel industry are on track to be down by 90%.

Capture in iron and steel industry: under the established Energy Technology Perspectives modelling framework, IEA proceeded to define Clean Technology Scenario (CTS, aggregate capture of 107 $GtCO_2$ by 2060) and Limited CO_2 Storage Scenario (LCS, aggregate capture limited within 10 $GtCO_2$ by 2060), analyzing the

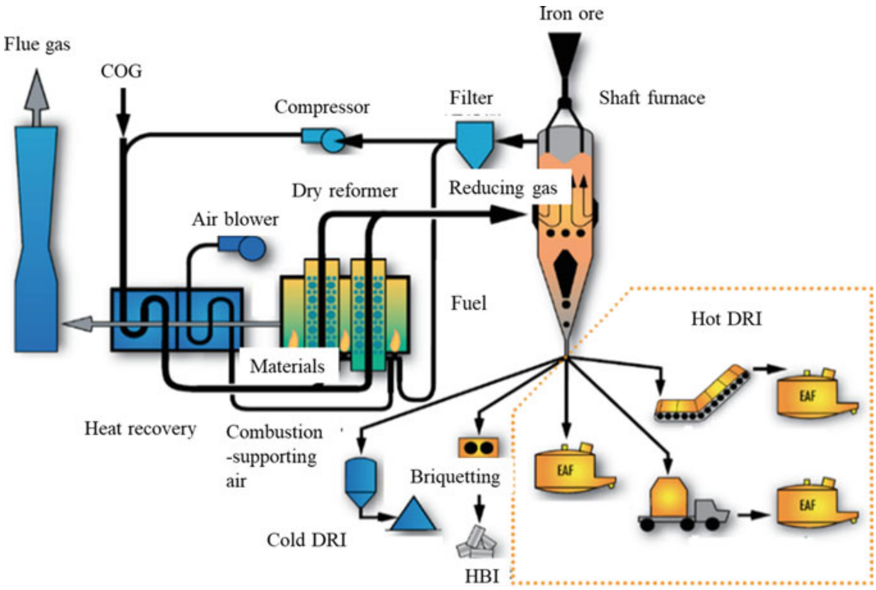

Fig. 7.23 Technical framework of steelmaking by CO_2-COG dry reforming. *Source* Zhou Hongjun, China university of petroleum

extra measures and technologies required for power, transport, industry and construction sectors under the two scenarios of CCUS technology application. CO_2 capture and utilization in various industries and sub-sectors under CTS scenario are illustrated in Fig. 7.24, which shows that for a considerable period, CCUS capture in iron and steel industry remained the mainstream of industrial CCUS, reaching around 1 billion tons by 2060 and accounting for approximately 44% of total emission from

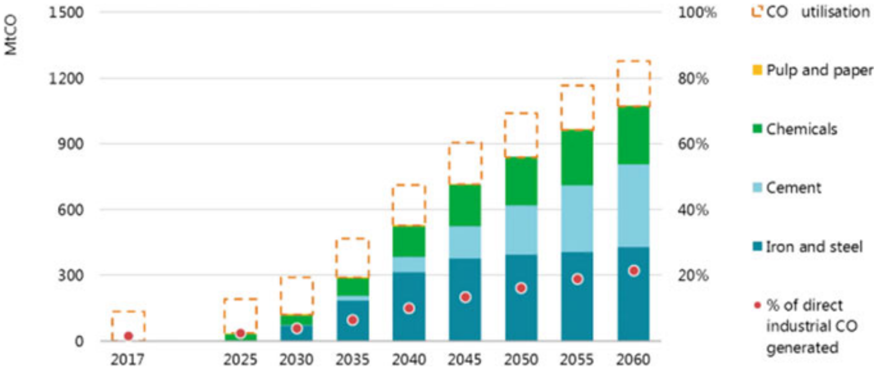

Fig. 7.24 Captured CO_2 for storage by industrial sub-sector and for utilization in the CTS. Notes CO_2 utilization refers to its application for the production of urea and methanol. *Source* IEA (2020), The Role of CO_2 Storage, IEA, Paris https://www.iea.org/reports/the-role-of-CO2-storage

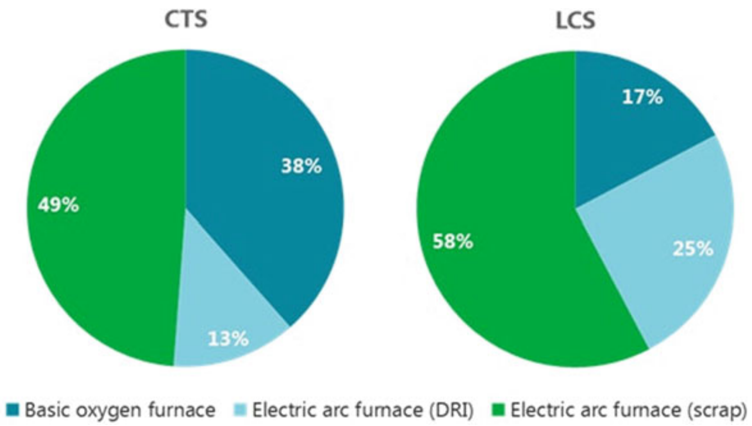

Fig. 7.25 Liquid steel production by process route and scenario in 2060. *Source* IEA (2020), The role of CO_2 storage, IEA, Paris https://www.iea.org/reports/the-role-of-CO2-storage

iron and steel industry. This means that iron and steel industry will remain a key area of industrial application of CCUS technology as it features concentrated production model and comparatively easier capture.

In LCS scenario, the entire industrial production structure must be transformed if the same level of emission reduction as in CTS scenario is to be achieved in iron and steel industry, as shown in Fig. 7.25. More radical technical improvements are needed to boost production efficiency; the proportion of scrap steel-short process steel must be increased to cut energy use/carbon emission in ore processing, sintering, palletizing, coking, etc., and innovative technologies must be scaled up (especially DRI-short process production technologies). According to IEA, in LCS scenario, DRI production would be dominated by hydrogen-based DRI by 2060, which will increase electricity use of the sector by 2.5 times compared to CTS by 2060. Massive tests are still required for hydrogen steelmaking, and demo projects in most countries and regions are set to be launched by around 2021. Therefore, from now to 2040, DRI production in LCS scenario would be less significant, and its prospects shall depend on its rapid development. In simple terms, the faster the development of CCUS technologies, the less investment needed for industrial transformation of iron and steel industry for carbon emission reduction under the same conditions.

7.4.2.2 Storage

According to *Technology Roadmap for Carbon Capture and Storage (2013)* by IEA, so long as fossil fuels and carbon-intensive industries predominate the economy, CCUS shall remain an important solution for GHG emission reduction. To make IEA's 2 °C scenario a reality, the specific goals and pathways by 2020, 2030 and 2050 were defined in the Roadmap (IEA 2013). It is expected that CO_2 capture will be applied in at least 30 projects of various sectors by 2020, including coal- and gas-fired power plants, natural gas processing and treatment, bioethanol and chemicals, hydrogen production in refining industry, etc. This means that all projects currently in the planning phase should be implemented on time and other projects should see major breakthroughs, with the annual CO_2 storage reaching 50 Mt. By 2030, CCS shall become a regular emission reduction technology in power industry and other industrial sectors with successful demo projects in multiple areas such as cement production, steelmaking BF, paper and pulp, secondary biofuel, etc. Such momentum shall drive CO_2 capture up to 2 billion tons/year. By 2050, CCS technology shall be a prevailing solution for carbon emission treatment in the power industry and all other industrial sectors worldwide, with over 7 billion tons of CO_2 stored.

7.4.2.3 Utilization

Zhu Rong's team in Beijing University of Science and Technology sought to tackle the two technological barriers in steelmaking, i.e. high CO_2 emissions and massive fumes, by adopting comprehensive CO_2 utilization technology (see Fig. 7.26) whereby the heat absorption effect of CO_2 reaction is used to reduce the fume and dust, and method using CO_2 as a resource in steelmaking was proposed. The physical–chemical essence of CO_2 used in steelmaking is systematically explained and the theoretical system created; the entire process is illustrated in Fig. 4.8. By far,

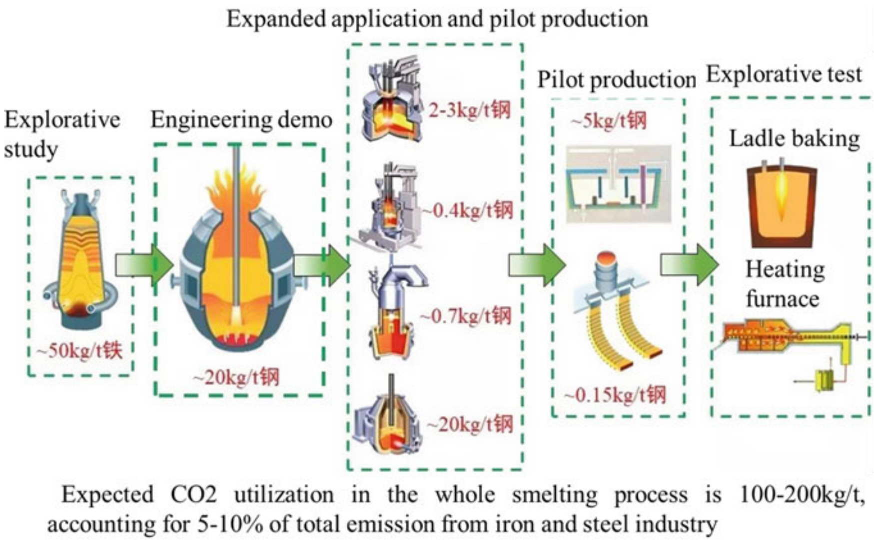

Fig. 7.26 Development plan of CO_2 comprehensive utilization technology and CO_2 utilization figures. *Source* Zhu Rong, Beijing university of science and technology

these technologies have been tried out in a demo project in Shougang Group (Jingtang) and extended to Tianjin Pipe and Xining Special Steel Co., Ltd. with satisfying outcomes. The R&D team is actively disseminating the method of using CO_2 as a resource in various upstream and downstream processes in iron and steelmaking industry such as sintering and palletizing, BF injection and LF/RH refining, etc. Besides, research is being conducted on combined coal gas CO/CO_2 production and utilization technologies for circular use of carbon element throughout the iron and steel smelting process. If achieved, it will cut CO_2 emission by 100–200 kg per ton of steel, or 5–10% of total emissions throughout the process.

Apart from the technology itself, the future development of CCS is also subject to the following factors:

(1) High cost. The expensive CO_2 capture is the main determinant of the total cost of CCS, and further cost reduction will depend on the maturing of technology. Opportunities in the interaction between international R&D peers should be fully utilized, with a blend of in-house R&D and overseas resources for continuous development of CCS technology;
(2) Lack of policy and regulatory framework. So far, few policies and regulations concerning CCS technology are in place, calling for more government efforts in this regard;
(3) Risk of leakage. Possible CO_2 leakage is the key safety concern, as CO_2 becomes immediately hazardous and even lethal at a mass fraction over 8. Although the probability of CO_2 leakage is rather low, precautions should be taken in all processes;
(4) Lack of public awareness. CCS technology is now little known to the majority of Chinese people, so a public awareness campaign is essential to introduce and promote successful cases, both local and overseas, to relieve the public concerns for leakage caused by CCS technology and build up trust and public support, which is an important preparation for more ambitious CCS development in the future;
(5) Inadequate evaluation criteria. Many components of CCS technology require evaluation. For example, the location for geological storage of CO_2 must be determined by overall assessment according to existing evaluation criteria. Poorly structured or conflicting evaluation criteria are likely to trigger a series of problems.

7.4.3 Carbon Reduction Cost

Of capture, transport, use and storage in CCUS, capture is the most expensive and energy-consuming part. The capture of high-concentration carbon source costs much lower than medium and low concentration sources. A typical medium to low concentration carbon source, carbon capture in iron and steel industry is quite costly.

Construction cost: currently, it costs around 27 million USD (approx. 190 million RMB) to install CO_2 capture and storage facilities of an annual capacity of 100,000 t in a steel plant (Jiang et al. 2021). According to the research results of China-UK (Guangdong) CCUS Center, taking Baosteel Zhanjiang Plant as an example, in order to launch a CCUS project of annual capture of 500,000 t for offshore storage in Beibu Gulf Basin within 100 k of the plant, the investment in a CCUS project of such scale in iron and steel industry would total at 360 million RMB.

Capture cost: with the capture cost of coal-fired plant as reference, post-combustion capture technology is the most mature in China and has entered into the engineering demo phase. It is mainly used in low-concentration coal-fired power plants. For Huaneng Group, the engineering cost is approximately 300 RMB/t of CO_2; the cost for Vanguard (Haifeng) Carbon Capture Test Platform launched in 2019, it was 500 RMB/t of CO_2. For oxygen-enriched combustion capture, the only lab-scale test and pilot test were conducted in a coal-fired power plant by Huazhong University of Science and Technology, with the cost respectively at 900 and 780 RMB/t of CO_2.

Transport cost: CO_2 transport within China usually depends on tank trucks at a cost of approximately 0.9–1.4 RMB/t CO_2·km. Jilin Oil Field has opted for pipeline transport at a cost of 0.3 RMB/t CO_2·km at a distance of approximately 20 km.

Total cost: based on the research results obtained by China-UK (Guangdong) CCUS Center, the economic evaluation results of Baosteel (Zhangjiang) Plant shows that the total emission reduction cost was 448 RMB/t CO_2 (Ren et al. 2019), much higher than Japan at 4000 yen/t CO_2 (approximately 264RMB/t $CO_{2.}$ In COURSE50 Project, however, the cost of both chemical/physical capture is likely to reach the goal of 2/000 yen/t (approximately 132 yen/t CO_2) (source: official website of COURSE50, https://www.jisf.or.jp/course50/outline/index_en.html).

7.5 Effectiveness of Low Carbon Technology Application in Iron and Steel Industry in China

7.5.1 *Analysis on CO_2Emissions from the Whole Life Cycle of Iron and Steel Industry*

A brief life cycle analysis was conducted by Ou Xunmin's team from Tsinghua University. With *China Iron and Steel Industry Yearbook 2016* (Editorial Board of China Iron and Steel Industry Yearbook 2017) and related publications (Zhou 2016; Yang 2017; Wang 2017) as a reference, the production process of primary and secondary iron and steel as well as the data on material and energy use of each process have been reviewed, including Source: Peng 2019.

The process of data collection and review is illustrated in Fig. 7.27 and Table 7.4, and explained as follows.

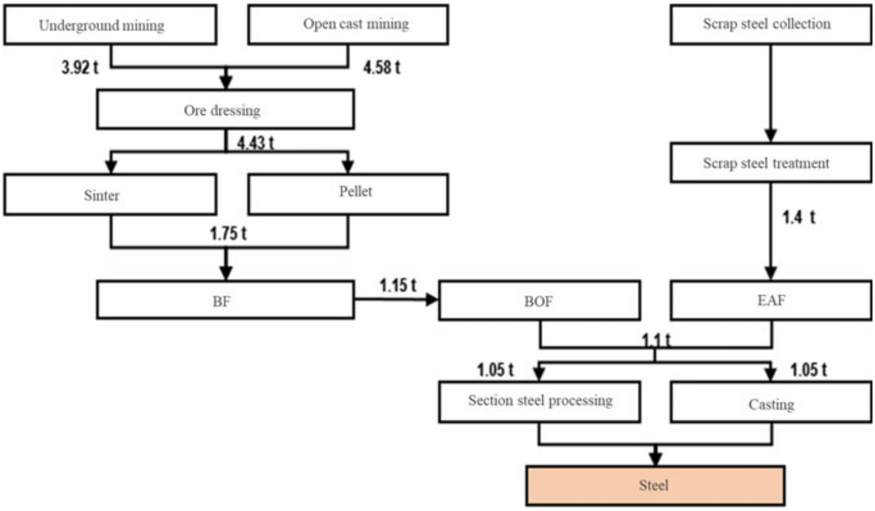

Fig. 7.27 Production flow of iron and steel materials and material consumption in each process. *Source* Peng 2019

7.5.1.1 Material Consumption

Material consumption means the consumption of raw materials or auxiliary materials of a process during the production of per unit mass of final products (t/t product). It is determined by the material enrichment in each process. Taking ores for instance, the mining of iron ores includes underground mining and open pit mining. Considering of ore grade, material recovery rate in smelting process and yield rate in processing, an output of 1t of steel for car-building requires 3.92 t of ores mined from underground and 4.58t from open pit respectively. In 2015, underground and open cast mining respectively comprised 23–77% of iron ores output in China, a weighted ore consumption being 4.43 t on average per ton of steel products.

Specific details of techniques and material consumption are as follows:

- BF technology: based on BF and BOF, main material input per ton of crude steel (approx.) includes: 1400 kg iron ore, 800 kg coal, 300 kg limestone and 120 kg scrap steel. Around 70% of steel in the world is produced with this method.
- EAF: main materials are scrap steel and /or DRI or molten iron and electricity. Main material input per ton of crude steel (approx.) is: 880 kg scrap steel, 300 kg iron, 16 kg coal and 64 kg limestone. 100% input of scrap steel is also possible with EAF method. Around 30% of steel in the world is produced with this method.
- Open-hearth furnace: this method accounts for around 1% of world steel production. It is being phased out due to poor environmental performance and economic viability.

Table 7.4 Process energy consumption intensity and fuel structure

Process	Energy consumption intensity (MJ/t)	Fuel structure (%)								
		Coal	Oil	Natural gas	Diesel	Gasoline	Fuel oil	Electricity	Coke	Coal gas
Underground mining	40.3	0	0	0	0	0	0	100	0	0
Open cast mining	13.8	0	0	0	77.1	0	0	22.9	0	0
Ore dressing	110.4	0	0	0	0	0	0	100	0	0
Sinter	1448.6	88.7	0	0	0	0	0	11.3	0	0
Pallet	506.7	75.1	0	0	0	0	0	24.9	0	0
BF ironmaking	14,300.2	26.2	0	0	0	0	0	1.7	72.1	0
BOF steelmaking	255.3	0	0	0	0	0	0	100	0	0
EAF steelmaking	1047.3	0	0	0	0	0	0	100	0	0
Finished steel processing	1866.4	0	0	0	0	0	0	21.6	0	78.4
Foundry casting	12,583.1	47.8	0	0	0	0	1.4	45.1	0	5.7

BF requires the partial use of scrap steel (a maximum of 35%). EAF can apply 100% of scrap steel but if 100% DRI is used, scrap steel would not be utilized. As scrap steel is insufficient at present, it is unrealistic to produce all new steel with recycled resources.

It should be noted that iron and steel products are simplified as finished steel, foundry iron and steel without elaborated taxonomy.

7.5.1.2 Process Energy Consumption Intensity

Process energy consumption intensity is defined as direct energy input per unit mass of product produced with a certain process, where product refers to the product of the process and is not necessarily the final one. Again, with iron ore as an example. In 2015, the energy consumption intensity of ore dressing was 110.4 MJ/t, i.e. 110.4 MJ of energy input is needed per ton of iron ore concentrate. Unit consumption multiplied by process energy consumption intensity equals energy use of the process, and the final energy consumption intensity of steel material for vehicles is the total of energy use of all processes. Iron ores are processed into crude steel product throughout dressing, sintering, palletizing, BF ironmaking and BOF steelmaking, and then processed into finished steel or foundry components as materials for vehicle spare parts. Compared to iron and steel produced by iron ores, the producing secondary iron and steel is less complicated, with recycled scrap iron and steel fed into EAF for smelting (WSA 2018). The results show that BF ironmaking, coking and EAF steelmaking rank the top in energy consumption, with correspondingly higher emissions.

7.5.1.3 Import, Export and Transport

About 87.5% of iron ores in China relied on import in 2015. For imported iron ores, energy consumption in the mining process is not considered, and the sea travel distance is the average distance from exporting countries to China weighted by their respective proportion in China's ore import. According to the statistics of customs and industrial association, the average sea travel distance of imported iron ores is 6652 nautical miles and the railway transport distance to iron and steel plants is set as 533 km, which is an average railway transport distance for metal ores (National Bureau of Statistics 2018). The means and distance of transportation of locally extracted ores are determined with reference to imported ores on arrival. Suppose the average distance between scrap steel hub and steel plant is 300 km by road transport. Suppose the processed iron and steel materials are transported to spare part manufacturer 200 km away by truck.

Table 7.5 Life cycle GHG emission of iron and steel materials

	Iron		Steel	
	Pig iron	Foundry iron	Finished steel	Foundry steel
kg CO_2, eq/kg	1.74	3.70	2.10	3.87

7.5.1.4 Analysis Results

The results are listed in Table 7.5. The GHG emission intensity of steel and iron in China is around 2 kg $CO_{2,eq}$/kg. Compared to long-process steelmaking (primary materials), short-process steelmaking (secondary materials) is in a better place of emission reduction. Cast iron and cast steel feature higher GHG emission in the entire life cycle.

7.5.2 Analysis on Effectiveness of Technical Improvement and Low Carbon Technology Application in Iron and Steel Industry

In recent years, the energy efficiency of iron and steel production in China has experienced notable improvement. According to the 13th Five-Year Plan, unit energy consumption of iron and steel shall be lowered to 560 kg standard coal per ton of iron and steel. The technologies elaborated in 7.2.2 are crucial for achieving this energy saving and emission reduction target within a short period.

7.5.2.1 Emission Reduction Potentials of Techniques

Researchers analyzed carbon emission potentials in different phases of iron and steel industry. As illustrated in Fig. 7.28, BF ironmaking, rolling, casting and steel making-EAF rank the top four techniques in emission reduction potential; in comparison, the potential of BOF-steelmaking is mediocre (Ren et al. 2019). This shows: (1) the development and dissemination of CCUS technology will slash direct emissions from BF; (2) clean power and technical advancement in production can further cut emissions from rolling, casting and ironmaking-EAF; (3) scrap EAF promises dramatic efficacity in emission reduction as it eliminates coking and iron making-BF; (4) For BOF, there is little space for emission reduction by technical improvement; a more viable option is to replace it with new techniques such as top gas recycle and hydrogen DRI.

Iron and steel industry itself still believe that technologies such as waste heat recovery (TRT etc.), advanced dry-quenching (CDQ etc.) are still useful in improving the energy efficiency of less developed iron and steel plants; while emerging technologies such as Jet BOF which, according to global data, can reduce power consumption

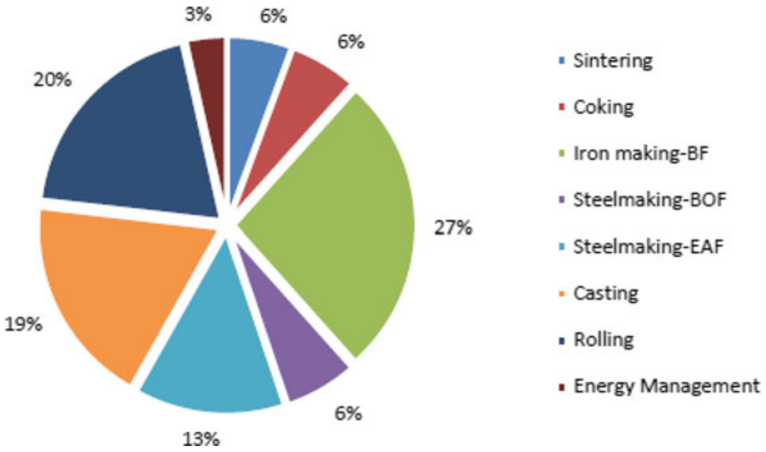

Fig. 7.28 Comparison of carbon abatement potential in different processes

by 60%, COG consumption by 37% and coal consumption by 16%. The Chinese government and Chinese researchers generally hold that it is crucial to continuously boost the energy efficiency of iron and steel industry; however, given that the overall energy efficiency is already raised to a high standard, it would be unrealistic to expect another 15–20% improvement of energy consumption and emission per ton of steel (on top-notch level) by further energy-saving efforts. Instead, revolutionary core production technologies are needed if zero net carbon emission is to be achieved in China.

7.5.2.2 Cost Analysis of Emission Reduction Through Technical Improvement

Researchers have analyzed the marginal abatement cost for renovative abatement options of iron and steel industry stated in the 12th Five-Year Plan, as shown in Fig. 7.29. Results indicated that the CO_2 abatement potential of the 25 techniques selected totaled 898 $kgCO_2/t$ of crude steel. In the case where all technologies illustrated in the Figure are adopted and promoted in China, an abatement of 43% can be expected from crude steel. Among these, the top 9 technologies in cost efficiency promise a total abatement potential of 426 $kgCO_2/t$ of crude steel, accounting for nearly 20% of CO_2 emissions of crude steel. Currently, over half of the renovative technologies are less economically viable, which, nevertheless, may offer better cost efficiency in the future with rising energy/carbon prices (Ren et al. 2019). Generally speaking, new technologies of waste heat recovery and reuse are economically viable with good abatement performance, hence better technical options cost-wise.

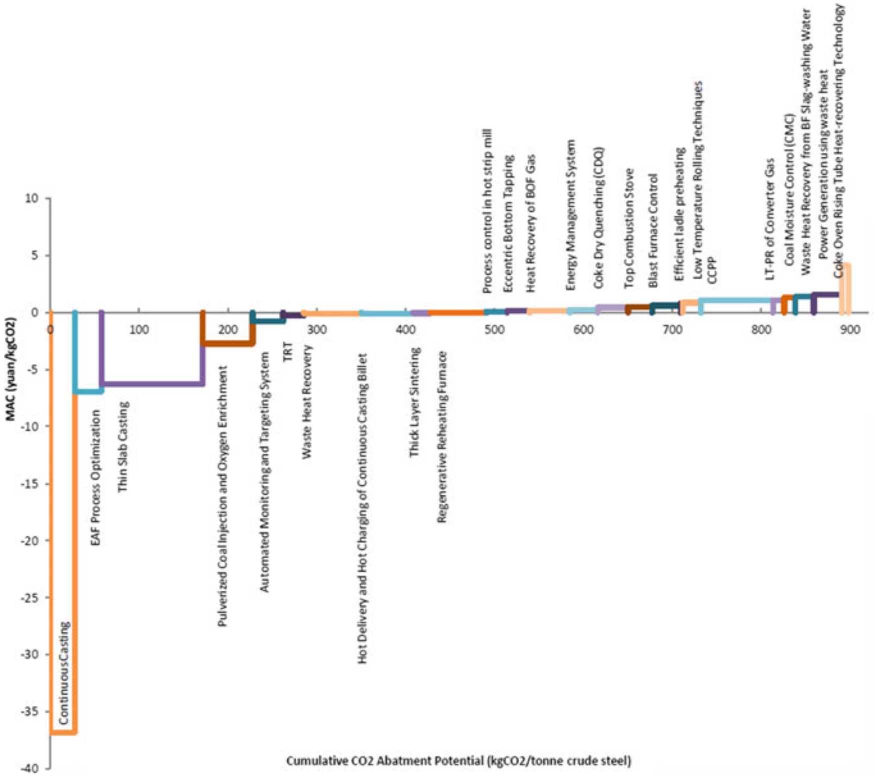

Fig. 7.29 Marginal abatement cost curve of a technology package of 25 abatement options for the iron and steel industry in China with a 15% discount rate. *Source* Ren et al. 2019

7.5.2.3 Plans for Technology Renovation and Promotion

Chinese researcher Ma Ding conducted an analysis on carbon emission peaks of various industries in China with China TIMES model. For iron and steel industry, calculations were made for 30 technical renovations (technologies such as latent heat recovery were taken into consideration, which was absent in Liang Xi's research) based on *Catalogue of Key Energy Conservation and Emission Reduction Technologies* published by NDRC, *Guide for Advanced Applicable Technologies of Energy Conservation and Emission Reduction* published by MIIT and *Catalogue of Key Low Carbon Technologies for National Promotion* published by NDRC in 2014. With these documents as well as energy-saving and abatement performance, applicable conditions, maturity, reliability, investment cost and economic benefits, market forecast and development potentials, etc., a development roadmap for low-carbon technologies was drawn as illustrated in Fig. 7.30 (Ma 2015). Priority should be given to technologies with lower application threshold and better cost effectiveness so as to achieve 100% penetration, including waste heat recovery from rolling steel,

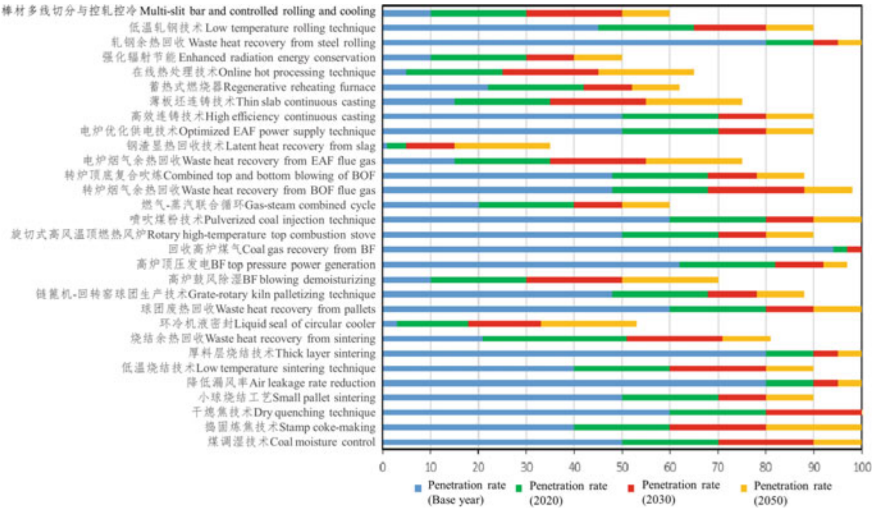

Fig. 7.30 Promotion targets of key technologies of iron and steel industry. *Source* Ma 2015

pulverized coal injection, BF coal gas recovery, waste heat recovery from palletizing, thick layer sintering, air leakage rate reduction, dry quenching, stamp coke-making, coal moisture control, etc.

7.5.3 *Analysis on Effectiveness of Zero Carbon Technology Application in Iron and Steel Industry*

7.5.3.1 Facilitating Low Carbon/Zero Carbon Development of Iron and Steel Industry with Zero Carbon Electricity

As illustrated in Fig. 7.31, it is estimated by Energy Transformation Commission that as the carbon intensity of EAF steel is far lower than BF steel in China, the increase in the share of EAF steel will automatically lower the average carbon intensity of iron and steel production. Even at the current carbon emission intensity of China's power sector (596 g CO_2/kWh), EAF steel is merely 0.5 tCO_2/t of steel, while the figure reaches around 2.1 t CO_2/t of steel for BF steel. Decarbonization of the power sector will gradually bring down the carbon intensity of EAF steel to zero. Therefore, two policies hold the key for decarbonization of China's iron and steel industry: first, continuously boosting the development of short-process steelmaking; second, supporting the expansion of power generation from renewables and nuclear; both of which being zero-carbon techniques. In the zero-carbon scenario, by 2050, the output of short-process EAF steel is expected to reach 333 Mt, which translates to zero-carbon power demand of 0.16 trillion kWh. Moreover, it is equally important

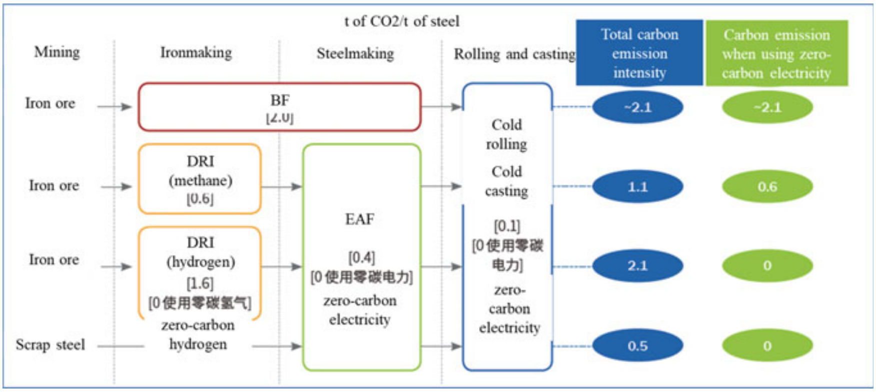

Fig. 7.31 Comparison of carbon emission intensity of BF-BOF, hydrogen/methane DRI and scrap steel short-process steelmaking. *Source* ETC 2019

to facilitate the development of waste recovery system through policy support and appropriate market incentives. It is estimated by study that annual scrap steel supply in China will reach 300–400 Mt by 2050, meeting the demand of short process steelmaking industry. Constraints on short process steelmaking are electricity price, availability of clean electricity and output of scrap steel (ETC 2019).

Methane/hydrogen (hydrogen generated by grid power) DRI steelmaking technique reports a total carbon emission intensity of 1.1/2.1 tCO_2/t of steel under the current technical conditions, showing no competitiveness in abatement compared to conventional steelmaking technique. However, a total emission of 0.6/0 tCO_2/t of steel can be achieved under zero carbon electricity conditions, which is close to zero emission. Here, hydrogen DRI steelmaking is not constrained by the scrap steel output, thus promising great prospect for application.

7.5.3.2 Assumptions of Effectiveness of Hydrogen Steelmaking and CCUS Technology Application

The relative cost of hydrogen DRI steelmaking technique and CCUS, in large measure, hinges on the price of zero carbon electricity used for hydrogen generation.

Comparison of application cost between hydrogen steelmaking and CCUS: As illustrated in Fig. 7.32, according to the analysis by McKinsey, for new projects, when the price of zero carbon electricity is below 45 USD/MWh (0.31 RMB/kWh), hydrogen DRI steelmaking would cost less than integration of CCS technology; for existing projects, the cost competitiveness of DRI will not be observed until the electricity cost goes below 25USD/MWh (0.18 RMB/kWh). With enormous capacity of BF iron and steel production in China, the CCS conversion of existing BF facilities would be more meaningful. Therefore, in the short term, CCS conversion projects are more economically viable. According to ETC forecast, with sufficient renewable

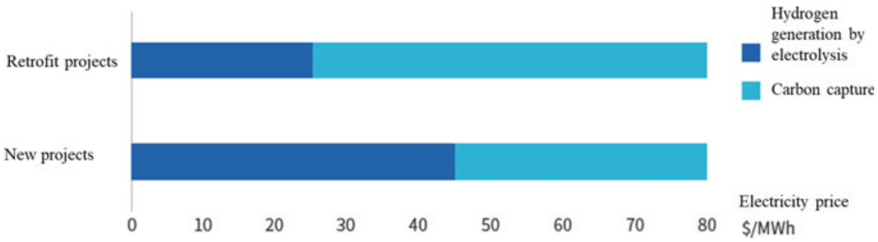

Fig. 7.32 Decarbonization cost of iron and steel production on the supply side. *Source* Vercammen et al. 2017

energy resources and adequate utilization system, China may see its electricity cost cut below 25USD/MWh before 2050, by which time hydrogen steelmaking will become an economically preferred option.

Future Prospects:

Abatement potential: global iron and steel production was approximately 1.8 billion tons in 2018; at CO_2 emission intensity of 1.8 t/t of steel per unit of steel products, total CO_2 emissions of iron and steel industry totaled around 3.2 billion tons. 50% abatement achieved by DRI technique in the current scenario will translate into at least 1.6 billion tons of CO_2 abatement. Furthermore, a combination of EAF and zero carbon electricity would mean an opportunity of 80% total abatement.

Hydrogen demand: China's crude steel production in 2018 was approximately 900 Mt (of which 800 Mt are from long process steelmaking), based on a hydrogen consumption of 50 kg per ton of reducing iron, approximately 40 Mt of hydrogen would be needed if it is used in all long process steelmaking facilities. Furthermore, a combination of EAF and zero carbon electricity would mean a total emission reduction of 1.6 billion tons of CO_2.

Analysis on effectiveness of application of hydrogen-DRI and CCUS technologies: suppose China's steel production in 2050 is 700 million, of which 40% is long process, emitting 560 Mt of CO_2 from 280 Mt of iron. Assume the coke cost per ton of steel is 0.5t*1200 = 600 RMB, based on the CCS cost of 450 RMB/t (with demo projects in 7.4.3 as a reference) in China's iron and steel industry, the cost of application of zero carbon technology in 2 °C scenario and 1.5 °C scenario is roughly calculated, and the results are shown in Table 7.6. For deep decarbonization of China's iron and steel sector by CCS or hydrogen technique application, the total abatement costs in policy scenarios corresponding to 2 °C and 1.5 °C are around 80 billion RMB and 250 billion RMB respectively.

Table 7.6 Estimated costs of deep decarbonization of industrial sectors in 2 °C scenario and 1.5 °C scenario

Iron and steel output in 2050 (100 million t)	Proportion of long-process		CO_2 emission rate (t/t of steel)		CO_2 emission (100 million t)	
7	40%		1.8		5.04	
2 °C scenario						
Option 1: CCS technology	CCS cost (RMB/t)					Total CCS cost (100 million RMB)
	400					Approximately 850
Option 2: Hydrogen steelmaking	Hydrogen consumption (t/t of steel)	Hydrogen cost (RMB/t)	Operational cost (100 million RMB)	Coke replaced (t/t)	Coke cost	Cost increase of hydrogen steelmaking (100 million RMB)
	0.055	Approximately 29,000	2246	0.86	1444.8	Approximately 800
1.5 °C scenario						
Option 1: CCS technology	CCS cost (RMB/t)					Total CCS cost (100 million RMB)
	500					Approximately 2100
Option 2: Hydrogen steelmaking	Hydrogen consumption (t/t of steel)	Hydrogen cost (RMB/t)	Operational cost (100 million RMB)	Coke replaced (t/t)	Coke cost	Cost increase of hydrogen steelmaking (100 million RMB)
	0.055	Approximately 35,000	5390	0.86	2889.6	Approximately 2500

7.6 Conclusions and Recommendations

7.6.1 Key Conclusions

(1) **Pressure exists in low carbon development of China's iron and steel industry**.

- Massive production and emissions: China, as "world factory", contributes to over 50% of the world's total iron and steel output. The progress in industrialization and urbanization are boosting domestic demand for iron and steel;
- Small proportion of short process steel: constrained by the reality, only a small portion of iron and steel output in China is attributable to short process ironmaking technique, which is difficult to reverse within a short time;
- Low concentration: approximately 20% of the production capacity is contributed by small- and medium-sized iron and steel plants, prompting a rise in average energy consumption/emissions;
- Risk of surplus capacity and excessive inventory: considerable surplus in production capacity and inventory is produced by incentives aiming at tackling economic crisis;
- Risk of industrial transfer and shrinking international trade: conservatism is rife in countries like US, attempting to lure back their overseas industrial establishments; while underdeveloped regions are gradually joining market competition as their economic growth picks up.

(2) **Multiple options and vast potentials are available for technical renovation**.

- **Multiple options for technical renovation and vast potentials for comprehensive abatement**: from both consumption and production side, multiple energy-saving and abatement technological options exist in every phase of iron and steel production, with total theoretical abatement of 43% by mainstream technology upgrade;
- **Excellent cost effectiveness of some renovative techniques**: recovery and reuse of waste heat and waste gas from ironmaking and technology upgrades in rolling/casting can reduce emissions while improving production efficiency, demonstrating desirable cost effectiveness.

(3) **Zero carbon technologies, with their respective competitiveness, have captured wide attention**.

- **Universality of CCUS**: be it traditional BF/BOF ironmaking or COG/syngas DRI, CCUS technology can slash carbon emissions;
- **Less material consumption by hydrogen steelmaking**: compared to material consumption from CCS process as well as material consumption and land occupation from CCS facility construction, material consumption from

  hydrogen steelmaking is mainly within the equipment manufacturing and is relatively less;
  - **High abatement effectiveness of clean power**: apart from providing abatement effectiveness for hydrogen steelmaking, the development of clean power also significantly reduces energy consumption and carbon emissions of short process steel, making it a possible option for zero carbon option for iron and steel industry;
  - **Vital importance of cost effectiveness evaluation of zero carbon technologies**: zero carbon technologies in iron and steel industry, on the one hand, are costly during the R&D and construction period, and on the other hand, depend on the overall industrial planning and support as a systematic engineering undertaking, of which the cost of trial and error can be significant; therefore, cost effectiveness evaluation is of crucial importance and merits further study.

(4) **Zero carbon development is possible for iron and steel industry**.

  - Theoretically, comprehensive application of upgraded techniques and zero carbon technologies can result in an abatement of 80–95%, indicating promising prospects.

7.6.2 Policy Recommendations

It is predicable that iron and steel industry, a major source of CO_2 emissions, will face mounting pressure of abatement amid worsening climate change across the world. With a massive number of iron and steel enterprises varying significantly in technological development and scale of production, China is challenged by an especially arduous task of CO_2 emission reduction which comes into two dimensions - short term reduction and long-term abatement.

7.6.2.1 Short Term Emission Reduction

- Management should be improved in iron and steel industry with rationalized organization of production, higher industrial concentration and elimination of outdated capacity.
- R&D and promotion of renovative techniques should continue in iron and steel industry to cut energy use and emissions of existing capacity to the level of developed countries.
- Scrap steel recovery should be encouraged while prompting recycling industry to get prepared for potential risks such as surplus capacity, excessive inventory, industrial transfer and shrinkage in international trade, etc.

7.6.2.2 Long Term Abatement

- Facilitate the substitution of traditional energy such as coal and coke by renewable energy in iron and steel industry and adjust the energy mix, thereby paving the way for zero-carbon EAF steelmaking/hydrogen steelmaking.
- Carry out more strategic analysis and adoption planning of zero carbon technologies such as hydrogen steelmaking/CCUS, etc. to mitigate the cost of trial and error.
- Conduct more theoretical research, equipment R&D and demo project construction of zero carbon technology to maintain the technological edge.
- CO_2 abatement in iron and steel industry is a comprehensive undertaking which requires holistic thinking of internal and external factors such as corporate development and environmental protection policies, etc., which is to be taken seriously by iron and steel industry.

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