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Re-electrification in China Under the Carbon Neutrality Goal

Shu Yinbiao[1], Xie Dian[2], Zhao Liang[2], Gao Yajing[2], Zhao Yong[2], Zhou Chaoyang[2]

1. China Huaneng Group Co., Ltd., Beijing 100031, China
2. Energy Research Institute of China Huaneng Group Co., Ltd., Beijing 100031, China

Abstract: As carbon peak and carbon neutrality are incorporated into the overall plan for the establishment of China's ecological civilization, electric power will play a more crucial role in guiding green development. Implementing re-electrification to implement clean energy replacement on the energy production side and electric energy substitution on the energy consumption side is crucial for China to meet its carbon peak and carbon neutrality targets on time. In this article, we study the notion of re-electrification and make a proposal to assist China in achieving low-carbon development through re-electrification, taking into account the country's fundamental national conditions and resource endowment. We analyze the evolution trend of energy and power in China under different scenarios using a research framework of terminal energy demand—energy conversion system—primary energy mix, while considering the factors of economy, technology, policy, and environment. We also discuss the prospects of re-electrification. According to the findings of the study, re-electrification will greatly increase carbon neutrality. By 2060, the share of non-fossil energy in total primary energy consumption, the proportion of clean energy power generation, and the share of electricity in total final consumption will be 80%, 90%, and 70%, respectively. As a result, we propose that China (1) coordinate the carbon budget and emission reduction paths of various industries, (2) catalyze economic and industrial upgrade, (3) promote scientific and technological innovation in key fields, and (4) improve power market and carbon market mechanism.
Keywords: re-electrification; carbon neutrality; energy transition; electric energy substitution

1 Introduction

Climate change has been a recurrent challenge confronting humanity. Many countries and regions in the world have set the aim of carbon neutrality and implemented several action plans [1–3]. China has long placed a premium on mitigating climate change and sticking to energy saving and green growth as top priorities. In 2016, China ratified the *Paris Agreement* and increased its nationally determined contribution on an ongoing basis. In September 2020, it was formally declared that carbon dioxide (CO_2) emissions would peak before 2030 and that China would aim for carbon neutrality by 2060 [4].

The key technical means of carbon neutrality initiatives is the transition to low-carbon energy, which is of enormous importance to national energy security, sustainable development, and economic growth [5]. The essence of the energy transition is the constant reduction of fossil fuel consumption and the vigorous development of renewable energy. For continued use, more than 90% of non-fossil energy must be converted into electric energy. Hence, re-electrification is the most important strategy for promoting the use of clean energy and achieving carbon neutrality. The connotation of re-electrification includes decarbonization, electrification, digitalization, and standardization. This involves the following processes: realizing clean substitution in the energy production field

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Corresponding author: Zhao Liang, professor-level senior engineer of Energy Research Institute of China Huaneng Group Co., Ltd. Major research direction is energy and power planning. E-mail: zhao_liang@chng.com.cn
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and increasing the supply of clean energy; promoting electric energy substitution in the energy consumption field and building a highly electrified society; empowering energy and power system through digitalization, achieving high perception, two-way interaction, flexibility, and efficiency; advancing scientific and technological innovation and achievement transformation through standardization, and constructing a carbon standards system following international standards, thereby accomplishing low-carbon technical advancement, industrial upgrading, and achievement sharing.

In the field of electrification, many scholars have carried out relevant research, such as strategic path, challenge, and potential analysis of electric energy substitution [6–8]. The essence of re-electrification is the efficient use of clean energy and the substitution of the direct consumption of fossil energy by electricity. It not only involves the transition and upgrading of the energy system itself but is also a broad and profound economic and social change [9]. Several studies have discussed the scientific validity and practicability of transition models such as electric energy substitution and multi-energy complementation from the perspective of price elasticity, technology diffusion, and China's economic growth [10]. Although most academics believe that the influence of renewable energy development is beneficial to social development, it is vital to distinguish across countries and regions for research and discussion [11].

In conclusion, to support the low-carbon transition of the economy and society, we must stick to a systematic approach, consider all relevant aspects such as energy, economy, and environment, and provide a rational and scientific development path. This study analyzed re-electrification's development necessity, key promotion fields, and major influencing factors in order to achieve carbon neutrality by 2060, constructed a model to study the path of re-electrification in China, and proposed countermeasures and recommendations.

2 Impetus of re-electrification

2.1 Environmental impetus

China is under increasing pressure to reduce local air pollution and CO_2 emissions. There is significant potential to establish synergistic control between the two because of their homology at the root and the similarity of their effects on measures [12]. Large-scale replacement of fossil energy with renewable energy is the primary measure. China is currently responsible for around 28% of the world's total CO_2 emissions. Hence, the goal of reducing CO_2 emissions is difficult. To reduce fossil energy consumption and environmental pollution, China must boost energy-saving measures and control industries with high pollution and high environmental risks, accelerate the development and use of renewable energy, and increase the electrification level.

2.2 Economic impetus

Globally, promoting economic development through energy transition has become a mainstream approach [13]. Over forty years of reform and opening up, China's economic development has reached a new stage. To boost industrial upgrading in China and change its pattern of economic development, it is vital to create new pillar industries and economic growth points. As a traditional fundamental industry, the energy system has a substantial effect on economic growth and industrial modernization. The energy business is an integral aspect of the national economy, but it also plays a vital role in the growth of other sectors. Currently, China must accelerate the adjustment of the industrial composition, reform, and upgrading. In September 2020, the National Development and Reform Commission and four other ministries issued a proposal to increase investment in strategic emerging industries and cultivate and expand new growth points and growth poles, such as in the new-generation information technology, high-end equipment manufacturing, and new energy industries [14]. The State Council issued the *New Energy Vehicle Industry Development Plan (2021–2035)* in November 2020, ushering in a period of rapid development for electric vehicles. The *14th Five-Year Plan and the Long-Range Objectives Through the Year 2035* [15] emphasized that it will accelerate the development of modern industrial systems, strategic emerging industries, and the digital economy as well as promote digital industrialization and industrial digitization. During the 14th Five-Year Plan period, the direct electricity demand of new infrastructure will reach 6.5×10^{11}–7×10^{11} kilowatt-hour (kW/h), accounting for 7%–7.6% of China's total electricity consumption. China's industrial adjustment and high-quality development will contribute to a rapid rise in electricity demand, which will serve as a significant impetus for the execution of re-electrification.

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2.3 Technical impetus

In the energy production field, clean energy power generation technologies, such as wind power and photovoltaics, are undergoing rapid growth. According to an analysis by the International Renewable Energy Agency, the levelized cost of energy (LCOE) of photovoltaics has decreased by 82% since 2010, making it the production technology with the most rapid cost reduction. Wind energy and solar energy have reached grid parity. The technology for generating electricity from coal with high parameters and ultralow emissions has been developed further. The study and development of zero-carbon or carbon-negative technologies, such as CO_2 capture, utilization, and storage (CCUS) and bioenergy with carbon capture and storage (BECCS), are intensifying. In the energy consumption field, electric vehicle battery life and power usage have improved dramatically. The average power consumption of pure electric passenger vehicles in China has decreased to 8.6 Wh/(100 km·kg), which has a clear impact on energy conservation, and the technology for fast-charging is constantly evolving. Clean heating technologies, such as high-efficiency heat pumps and regenerative electric boilers, are being increasingly advocated for and implemented. Moreover, significant advancements in technologies such as intelligent electricity consumption, innovative energy storage, intelligent energy management, and demand response have provided technical support for the development of re-electrification.

3 Main implementation fields and key influencing factors of re-electrification

3.1 Main implementation fields

Re-electrification is predicated on the efficient exploitation of renewable energy [16]. The implementation fields comprise most of the industries, buildings, and transport sectors as well as the energy conversion-carrying power sector. As seen in Fig. 1, the power sector converts clean energy into electricity on a wide scale, whereas the industry, building, transport, and other sectors increase the scale and scope of power usage to achieve highly efficient development and exploitation of clean energy.

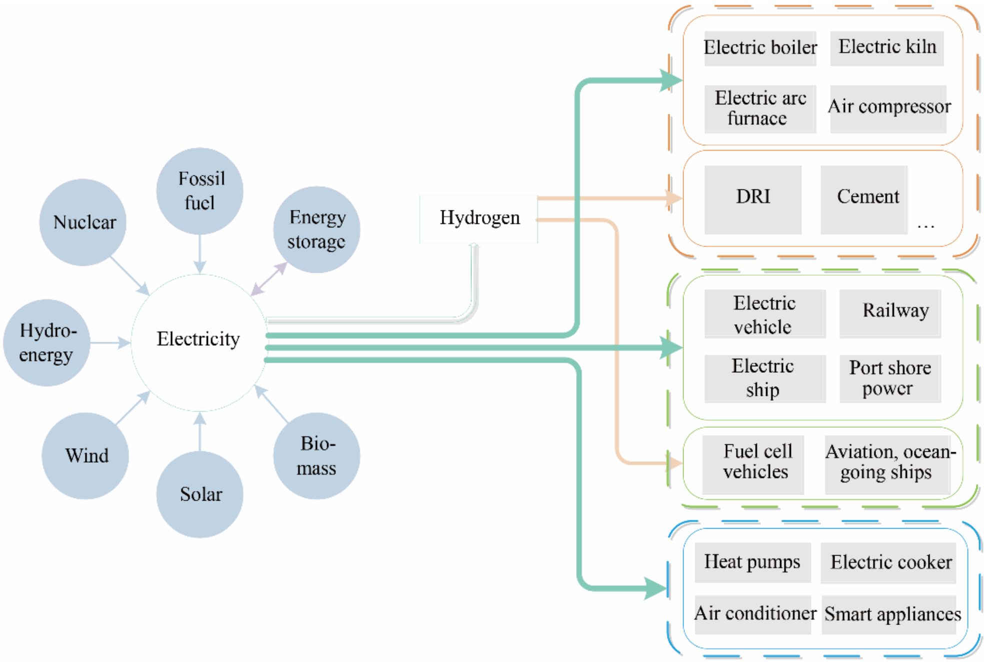

Fig. 1. Main implementation fields of re-electrification.

3.1.1 Industry sector

Presently, the energy consumption of the industrial sector accounts for more than 60% of the total final energy consumption, with fossil fuels dominating. Its CO_2 emissions contribute 37% of the overall volume caused by energy consumption, whereas electricity only accounts for 26%. Energy-intensive and high-emitting industries, such as steel, cement, and chemical industries, are the focal point of industrial emission reduction and are also significant fields of electric energy substitution. Future improvements in energy efficiency and electrification should be made to ease the demand for fossil fuels.

3.1.2 Building sector

The energy consumption of building sector is mainly used for space heating and cooling, lighting, cooking, operating household appliances, and water heating, including electric energy and thermal energy, and the thermal requirement of the building industry consists primarily of low-grade thermal energy, which can be easily fulfilled by high-efficiency heat pumps, electric boilers, and other technologies. The present share of electricity in the total final energy consumption of building sector has surpassed 40%, making it the most electrified sector. However, there is still substantial potential for further improvement. Substituting electricity for coal, oil, and natural gas will dramatically reduce CO_2 and pollutant emissions.

3.1.3 Transport sector

The transport sector consists of roads, railways (including urban rail transit), shipping, aviation, and pipelines. Petroleum dominates energy use, while electricity accounts for less than 4%. Currently, it holds the greatest percentage of fossil fuels among all terminal sectors. The roads consume the most energy in the transpor sector. The rapid development of new energy vehicle is expected to attain a high level of electrification and significantly reduce the use of fuel-powered vehicles. Currently, the electrification rate of railways exceeds 70%, and in the future, electric energy substitution will be promoted rapidly. Electricity can also play a part in port-shore power and short-distance transit for shipping and aviation.

3.1.4 Power sector

Currently, power systems are the sector that emits the most CO_2. It is also a platform for energy conversion and a vital link between the energy production and consumption sides. It will play a significant role in the widespread and efficient use of clean energy and the achievement of carbon neutrality goal for China. In the future, nuclear energy, hydraulic energy, wind energy, and solar energy will be converted to electricity on a large scale, forming a multi-energy synergistic, interconnected, and integrated low-carbon power system. On the consumption side, the benefits of clean, efficient, flexible and convenient electricity will be utilized extensively to achieve deep energy conservation and emissions mitigation.

3.2 Key influence factors

3.2.1 Industrial mix

Tertiary industries have a significantly lower energy intensity than secondary industries. Energy-intensive industries, such as steel, cement, and ethylene, have a high energy consumption per unit of production, and their energy demand is primarily satisfied by fossil fuels. It is crucial to promote the optimization and upgradation of these industries by improving the electrification level. The energy demand of emerging industries such as high-end manufacturing, the service industry, new-generation information technology, and industrial Internet is mainly electricity, and thus their growth will contribute to China's overall electrification level.

3.2.2 Energy efficiency

Improvements in energy efficiency are intrinsically linked to energy-saving management and technological development. With an increase in the level of energy conservation, residual energy can be fully collected and utilized, hence reducing the total demand for end-use energy. Among the different end-use energy technologies currently available, electricity utilization efficiency is the highest; therefore, increasing electricity consumption has become an important measure for improving energy efficiency.

3.2.3 Electric energy substitution technology

Large-scale implementation of electric energy substitution technology will directly accelerate electrification. Electric energy substitution technology can be utilized in numerous industries, including the industry, building, and transpor sectors [17]. From a technical standpoint, most sectors and scenarios can use electricity to replace fossil fuels, and technologies such as electric vehicles, heat pumps, electric boilers, and electric kilns are maturing. From an economic point of view, the current cost of electricity is still high; electricity does not currently have a price advantage [18]. In future, it is expected to make electricity more economical with the decreasing of the LCOE of renewable energy power generation and the enhancing of its price competitiveness compared with fossil fuels through the carbon market.

3.2.4 Development and application of hydrogen energy

The future usage of hydrogen energy, biofuels, and other synthetic fuels will increase in industry, building, transport, and other sectors [19]. In certain situations when low-grade energy is primarily required, biofuels can be

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used directly. In addition, hydrogen energy and biofuels will play complementary roles in applications that require high energy density and in which direct electrification is difficult. With the steady maturation of "green hydrogen" preparation technology, an increase in the proportion of hydrogen energy will also increase the electricity demand, indirectly encouraging electrification.

3.2.5 Development and utilization level of non-fossil energy

On the energy production side, re-electrification is accomplished primarily through the large-scale development of non-fossil energy power generation, particularly wind power and solar power generation. The key to achieving energy transitions [20] is the high-quality development of new energy. Deep re-electrification is contingent upon a lower LCOE for new energy power and the friendliness of merging users In addition, advanced hydropower and nuclear power technologies will play a significant role in the re-electrification of energy production.

3.2.6 Zero-carbon or negative-carbon technologies (CCS/CCUS and BECCS)

Controllable power sources, such as coal-fired power, play a significant role in assuring the security of the power system and supporting the growth of variable power sources, such as new energy sources, based on anticipated technical advancements. CCS/CCUS-equipped coal-fired or natural gas-fired power production facilities can significantly reduce CO_2 emissions. Therefore, CCS/CCUS technology is expected to rapidly advance to meet the carbon neutrality goal. In addition, BECCS technology can be used to generate negative carbon emissions while encouraging biomass power generation, which partially supports essential fossil energy uses.

3.2.7 Carbon market and power market construction

The carbon market is a crucial market-based instrument for steering social emissions mitigation. Foreign development experience demonstrates its importance in promoting green transition [21]. In 2013, China launched local pilot projects of carbon market in seven provinces and cities. In 2021, the national carbon market was fully implemented and became the world's largest carbon market for covering CO_2 emissions. China has devised a series of policies on the national carbon market construction. In the future, the quota will gradually change from free distribution to paid distribution, thereby enhancing the comprehensive competitiveness of renewable energy and encouraging the improvement of the electrification level.

The power market also plays an essential role in promoting the incorporation of new energy, maximizing the frequency and peak shaving services of coal-fired power, and maximizing the demand-side load responsiveness, such as electrical vehicles. China has constructed 32 provincial power-trading centers and 2 regional power-trading centers. Currently, power market transactions are primarily based on the direct transaction of energy, and the capacity market and auxiliary service markets require further development [22].

4 Re-electrification path

4.1 Research framework

The final energy consumption mix can be predicted by taking into account factors such as technology, economy, environment, and policy as well as parameters such as macroeconomic development, industrial structure adjustment, population change, urbanization rate, and energy substitution. Furthermore, based on the energy resources endowment, the current state of power generation, and installed capacity, the maturity and development trends of energy conversion technologies (including power generation, heating, and hydrogen production) and energy storage technologies should be analyzed, and the constraints of energy security, CO_2, and pollutant emission are also taken into account to obtain the optimal primary energy supply mix and energy processing capacity (mainly reflected in the power generation mix). The prospects and paths of re-electrification in China are proposed in the preceding paragraphs.

4.2 Performance indicators

The main distinction between re-electrification and traditional electrification are its goals of constructing a clean, low-carbon, safe, and efficient energy system (with electricity as the platform hub), realizing the exchange and conversion of various energy sources, and achieving high-quality economic and societal development. The share of energy used for power generation in primary energy consumption and the share of electricity in total final consumption are traditional electrification performance indicators. Owing to the distinction between the implications of re-electrification and traditional electrification, re-electrification not only raises the share of electricity in total final energy consumption, but also realizes the entire energy system's low carbon and high efficiency. As a result, its characteristics can be classified into four dimensions: decarbonization of power production, amount of power consumption, power system safety and dependability, and economical and efficient use of electricity. Table 1 shows how the four qualities were used as evaluation dimensions to build the re-electrification performance indicator system.

Table 1. Performance indicators of re-electrification.

Evaluation dimensions	Performance indicators
Decarbonization of power production	Share of energy used for power generation in primary energy consumption
	Share of non-fossil energy power generation
	Share of renewable energy power generation
	CO_2 emissions per unit of power generation
Extent of power consumption	Share of electricity in total final consumption
	Share of P2H-containing electricity in total final consumption
Safety and reliability of power system	Power-gotten index
	Average power supply reliability
	Energy self-sufficiency rate
Economical and efficient use of electricity	Energy consumption per unit of GDP
	Electricity consumption per unit of GDP
	Average electricity price

The first six items in Table 1 are important indicators indicating the fundamental meaning of re-electrification and the last six items are auxiliary indicators reflecting the economic and social benefits of re-electrification. So, the first six items indicators should be used as the major evaluation basis in quantitative research of re-electrification.

The indicator of share of P2H-containing electricity in total final consumption (expressed in α) is used to clarify the role of electricity as a conversion energy in the future, where some energy produced by electricity is transformed into consumed electric energy. The calculating formula is as follows:

$$\alpha = \frac{P_\mathrm{h}}{E_\mathrm{end\text{-}use} - H + P_\mathrm{h}}$$

$E_\mathrm{end\text{-}use}$, H, and P_h indicate the total final consumption, hydrogen created by electricity, and electricity utilized to generate hydrogen, respectively.

4.3 Scenario assumptions

China will promote energy transition and economic mix modifications to achieve carbon neutrality by 2060. At the moment, the carbon sink stock of forests and oceans is only 6×10^8–7×10^8 t, and it is anticipated that the carbon sink will not exceed 1.5×10^9 t by 2060, despite a potential increase of the biological carbon sink. Furthermore, because there is no efficient solution to reduce CO_2 emissions from industrial processes or non-carbon dioxide greenhouse gases, ecological carbon sinks will be mostly devoted to these domains. As a result, we can only keep a minimal percentage of fossil energy use in the future while working to construct a new zero-carbon power system. By 2060, the CO_2 emitted by thermal power plants will be reduced by building CCS/CCUS and BECCS. Table 2 shows the assumptions connected to the scenario.

4.4 Evolution path

4.4.1 Energy and power supply mixes under carbon peak and carbon neutrality goals

In terms of primary energy consumption, non-fossil energy and energy utilized for power generation will expand significantly. There are numerous non-fossil fuel energy sources available. In addition to wind energy and solar energy, which are mostly used for power generation, direct thermal utilization of solar energy, geothermal energy, and biomass direct utilization are also included, which will eventually form the majority of primary energy. Owing to increased power substitution on the energy consumption side, electricity demand will continue to climb, primary energy directly used for final consumption will decrease, and the fraction of energy used for power generation will increase. Fig. 2 depicts the variance trend in China's primary energy consumption mix. The shares of non-fossil energy and energy utilized for power are 16% and 47% in 2020, respectively, and are predicted to

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rise to 28% and 57% in 2030 and 85% and 91% in 2060, respectively. Total primary energy consumption is expected to peak at 5.7×10^9 tce around 2030, before falling to 4.8×10^9 tce in 2060.

Table 2. Key influence factors and assumptions.

Items	Assumptions
Economy and population	The economic growth rate will be 5% or more before 2035. Then, it will gradually slow down to 3% to 4%. The population will reach a peak of 1.43 billion people around 2030. Then, there will be negative population growth; the population will drop to 1.34 billion and 1.28 billion in 2050 and 2060, respectively. Urbanization rate will reach 70% in 2030 and stabilize after reaching 80% in 2050.
Industry mix	The proportion of energy-intensive industries will be reduced, and high-end manufacturing and service industries will be vigorously developed. In 2060, the proportion of the tertiary industry will reach 70%, the proportion of terminal industrial energy consumption will drop below 50%, and the proportion of energy consumption in building and transport will continue to increase.
Energy utilization efficiency	The circular economy will be vigorously developed and the production process will be upgraded. Energy-saving renovation and green building will be promoted and building HVAC energy consumption will be reduced by 50%. The transport structure will be optimized further, and the proportion of high-efficiency and low-consumption vehicles will be rapidly increased.
Electric energy substitution	There will be further efforts to replace electricity in the fields of industrial equipment, building heating, and roads transportation. The amount of electric vehicles are expected to reach 360 million by 2060.
Technical advancement	After 2030, CCS/CCUS technology will be commercialized in some coal power, industrial process, and other fields. Hydrogen production from renewable energy will be rapidly applied after 2030. In 2060, the cost of solar power, onshore wind power, offshore wind power, and new energy storage will drop to 1800 CNY/kW, 3800 CNY/kW, 7000 CNY/kW, and 700 CNY/kW, respectively.
Energy and environmental policies	According to the carbon peak and carbon neutrality goals, the upper limit of carbon dioxide that can be emitted will be determined and carbon emission control goals for each stage will be set. In 2030, carbon dioxide emissions per unit of GDP will drop by over 65% compared with 2005 and the installed capacity of new energy will reach over 1.2×10^9 kW.

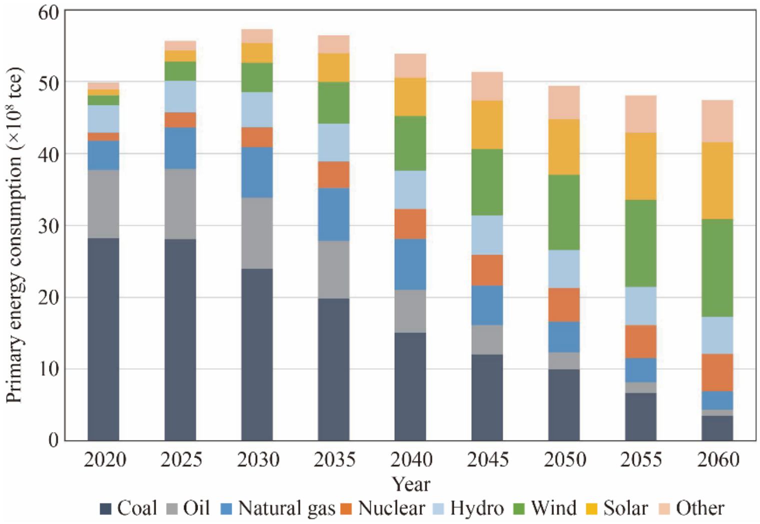

Fig. 2. Primary energy consumption mix in China.

Accelerating CO_2 emission reductions in power systems is the primary driver for China's low-carbon transition. China's power system's CO_2 emissions amounted to 38% of total national emissions in 2020, with non-fossil energy power generation accounting for 34%. To achieve carbon peak and carbon neutrality, we must energetically push low-carbon power generation while also coordinating power security and clean development. We will build a large clean energy base with multi-energy complementation in the northern and western regions, vigorously develop offshore wind power and distributed energy in the eastern and central regions based on local conditions, actively develop hydropower in the southwest region, and orderly develop nuclear power under the premise of ensuring safety. Facilitating the functional transfer of thermal power from the main body of electric energy supply to the main body of electricity supply will catalyze the research and development (R&D) and application of CCUS technology, and encourage the development of the power system toward zero carbon.

Before 2030, the CO_2 emissions from the electricity system will peak at around 4.5×10^9 t and then significantly fall following a 3–4 year plateau period. By 2060, zero-carbon emissions from power systems will be achieved. Fig. 3 depicts the variance trend in China's power-generating mix. In 2030, total overall power generation will be 1.18×10^{13} kW·h, with non-fossil energy power generation accounting for 49% and new energy power generation accounting for 26%, respectively. In 2060, total power generation will be 1.57×10^{13} kW·h, with non-fossil energy power generation and the new energy power generation accounting for 90% and 64%, respectively, and the installed power capacity will be 7×10^9 kW, with new energy installed capacity exceeding 5×10^9 kW.

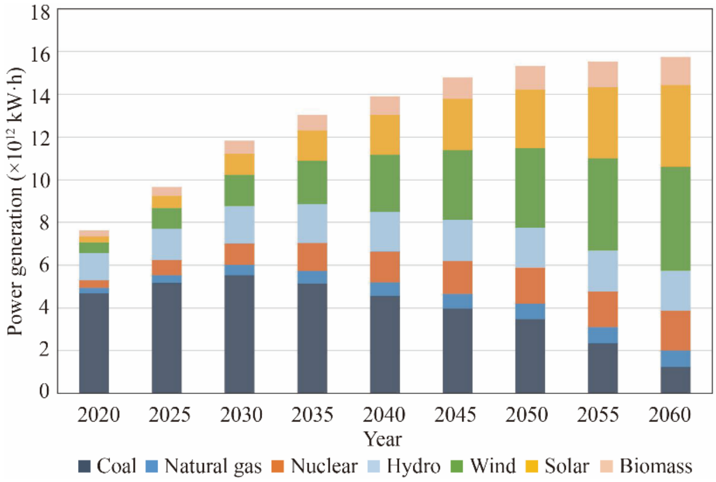

Fig. 3. Power generation mix in China.

4.4.2 Development trend of electrification level

The total final energy consumption is predicted to drop steadily, while the industrial mix will be gradually optimized, and the energy efficiency will also be significantly enhanced. China's total final consumption was around 3.5×10^9 tce in 2020, with industry, building, transport, and other sectors accounting for 61%, 22%, 14%, and 3%, respectively. With the continuous elimination of backward production capacity, the improvement and stabilization of the urbanization rate and the reduction of demand for energy-intensive products such as steel and cement, high-end manufacturing, the information technology industry, and the service industry will become the main consumers of terminal energy in the future. The share of energy consumed by industry will continue to fall, whereas the share of energy consumed by the building and transport sectors will rise steadily. China's total final energy consumption is expected to be 2.2×10^9 tce by 2060, with industry, building, transport, and other sectors accounting for 49%, 27%, 22%, and 2%, respectively.

Electricity will become the dominating energy for final consumption. CO_2 emissions from terminal fossil fuel burning account for more than half of the total energy emissions. With the strong promotion of low-carbon transition, we must expedite the substitution of coal, petroleum, and natural gas with electricity. Fig. 4 depicts the trend of the final energy consumption mix. It is estimated that by 2060, electricity would account for 70% of total final consumption. In industry sector, it is necessary to popularize the use of electrical equipment such as industrial electric furnaces and high-temperature steam heat pumps, so as to improve industrial electrification level and energy efficiency and increase green energy consumption. The building sector should actively push for the electrification of space cooling and heating, enhance the market-oriented transformation mechanism, and encourage the use of building roofs and walls for the development of distributed optical storage systems. Future transportation energy systems will be comprised of vigorous growth of electric vehicles, railways, port shore power, etc. in transport sector. By 2030, the share of electricity in total final consumption in industry, building, and

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transport sectors is expected to be 40%, 51%, and 10%, respectively, and by 2060, these shares will rise to 71%, 81%, and 54%, respectively.

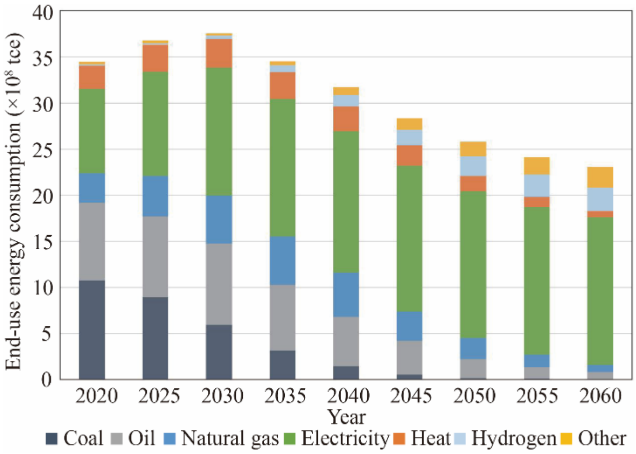

Fig. 4. Final energy consumption mix in China.

In scenarios where direct electrification is difficult to achieve, CO_2 emissions reduction is accomplished primarily through the replacement of low-carbon energy sources, such as green hydrogen, biomass, or fossil energy equipped with CCS/CCUS. In the sphere of intense energy production, it is difficult for electricity to replace fossil fuels. In the industry sector, it is difficult to substitute electricity for coal in the operations of blast furnace ironmaking, sintering, cooking, etc. Electric kilns cannot replace cement calcination kilns that are powered by coal. Many chemical products, such as soda ash, caustic soda, and synthetic ammonia have a high thermal demand that is still challenging to supply. The majority of the energy needs of light industries can be met through electrification. In the building sector, although it is difficult to use electric energy for heating in severely cold regions, electrification can be promoted in a variety of scenarios. In the transport sector, although electric heavy trucks and electric ships have been used and electric aircraft are also in development, they are expected to be used primarily for short-distance transportation and it remains challenging to electrify long-distance heavy-haul road freight, ocean-going ships, and long-distance aviation. In terms of feedstock, CO_2 emissions cannot be eliminated by electrification and low-carbon feedstock must be produced to reduce emissions. By 2060, electricity-produced hydrogen will account for 10% of the total final consumption, while electricity containing P2H will account for more than 80% of total consumption.

4.5 Comprehensive benefits

Re-electrification helps to improve energy utilization efficiency. On the energy consumption side, electric equipment is far more efficient than any other energy-consuming equipment. The efficiency of an electric kiln, for example, can surpass 85%, but that of a coal-fired kiln is just 30%. The coefficient of performance of the heat pumps for space heating is 3–5, whereas the efficiency of conventional coal-fired boilers is typically less than 80%. The electric vehicle consumes just about 20 kW·h per hundred kilometers, whereas the same type of fuel vehicle consumes 6–8 L of fuel every hundred kilometers (equivalent to about 50–70 kW·h). Even when losses in the power generation process are accounted for, increasing the electrification level in many application areas yields energy-saving benefits. With the increasing share of renewable energy power generation, the role of re-electrification in improving the efficiency of comprehensive energy utilization will be more prominent if it is converted using the electrothermal equivalent method.

Re-electrification is the primary method of utilizing non-fossil energy at large scale, which is conducive to achieving centralized carbon management and decarbonization and fostering carbon neutrality. In energy production field, electricity is the hub of energy interconnection and integration, the heart of clean energy systems, and the sole energy source that can be converted directly and in large quantities to other energy sources. In energy consumption field, reducing CO_2 emissions and pollutants by replacing the direct use of fossil fuels with renewable energy and modifying the energy consumption pattern of traditional sectors is effective. In 2020, China's CO_2 emissions caused by energy use were approximately 9.9×10^9 t and the direct CO_2 emissions of final energy consumption were 5.7×10^9 t. Through decarbonization of the power system and electrification of final energy consumption, CO_2 emissions will be rapidly reduced. Re-electrification will lead to over 80% of CO_2 reduction towards China's carbon neutrality goal.

Re-electrification will foster high-quality economic growth and provide extensive benefits for industry, employment, and the environment. Electricity significantly contributes not only to economic growth but also to the integration of energy technology and digital technology, fostering scientific and technical advancement and industrial upgrading. Re-electrification will also improve air quality and human health, reduce extreme climate events and medical expenditures, increase labor supply, enhance economic and social development, and lower the social cost of carbon. From 2020 to 2060, it is anticipated that the total investment scale for re-electrification would reach one billion CNY, effectively promoting the linkage between upstream and downstream industries and driving the transformation and upgradation of the equipment and manufacturing industries. Re-electrification will generate 10 million jobs by 2060. As the negative externality of CO_2 emissions is mitigated, the environmental benefits are expected to exceed 100 billion CNY. With the joint promotion of industrial optimization and upgrading, energy mix adjustment, and re-electrification level improvement, energy consumption and carbon emissions per unit GDP will decrease by over 80% and 92%, respectively, compared to 2020.

5 Key conclusions and recommendations

5.1 Key conclusions

This study proposed the notion of re-electrification, including decarbonization, electrification, digitization, and standardization, with the goals of carbon peak and carbon neutrality. The re-electrification performance indicators were established based on traditional electrification performance indicators, which highlight the function of electricity in encouraging green development and serving as the conversion hub of energy systems.

A quantitative analysis of the evolution process of China's re-electrification was undertaken, and scenario parameters were established to investigate the path of China's re-electrification towards carbon neutrality. China's energy system will achieve the goal of "70/80/90" by 2060, which means that the share of electricity in total final consumption will reach 70%, the share of non-fossil energy in total primary energy consumption will exceed 80%, and the proportion of clean energy power generation will exceed 90%.

Non-fossil energy power will be produced on a large scale. As a high proportion of new energy access will pose huge challenges to the security of the power system, it is estimated that a certain number of coal-fired and natural gas generating units will need to be retained to achieve emergency standby, guaranteed supply, peak regulation, and frequency modulation. Furthermore, the CO_2 emissions generated will need to be removed using CCUS. Substituting electricity for energy will be vital. By 2060, the share of electricity in total final consumption in industry, building, and transport sectors will reach 71%, 81%, and 54%, respectively, producing a clean, low-carbon, safe, and highly efficient energy system focused on electricity.

Re-electrification will increase economic and social development, energy efficiency, and significantly mitigate CO_2 emissions. However, it still faces economic, technological, market, institutional, and other hurdles. All regions and industries must encourage clean and low-carbon development and tackle significant electricity substitution technology concerns to construct an adequate industrial environment and promote the country's low-carbon development.

5.2 Recommendations

5.2.1 Strengthening top-level design and facilitating low-carbon power system transition

We recommend that the CO_2 emissions budgets of various sectors should be coordinated, considering the carbon emissions transformation induced by electric energy replacement, and the power system's carbon budget should be clarified. Clean development and energy security should synergize with low carbon power system transition. In the short term, coal-fired power is still an important guarantee of the power supply in China. In the medium- and long-term, the share of coal-fired power will drop sharply, and it will play the role of flexible regulation. Policies should be formulated to adapt and link with each other in different periods to ensure the transition of the coal-fired power function orientation. We should make full use of diversified clean energy and demand-side resources to ensure a balance between power supply and demand. When planning the power system, we should reasonably consider the confidence level of the new energy output power and encourage it to participate in the power balance scientifically and reasonably. Given the full role of the power grid as the energy conversion hub and basic platform, we should accelerate the improvement of a strong smart grid with ultra-high voltage as the

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backbone grid and strive to build a highly reliable, interactive, friendly, and cost-effective active distribution network.

5.2.2 Prioritizing energy conservation and accelerating industrial and economic restructuring

To improve energy conservation and efficiency, we should optimize the industrial mix and encourage high-efficiency energy technologies like electrification. We should accelerate the economic and industrial transformation and upgrading, strictly control the disorderly expansion of industries that have high energy consumption and high environmental risks, reduce backward production capacity, promote traditional industries to be high-end, intelligent, and green, and accelerate the development of new-generation information technology, new energy, new materials, high-end equipment, and other strategic emerging industries. Moreover, we should develop integrated energy services and widely promote key energy-saving and low-carbon technologies and industrial electric furnace applications in the industry sector. We should deepen building energy-saving renovation, increase the proportion of green buildings, develop distributed energy in buildings, and achieve low-carbon development in the building sector. Furthermore, we should accelerate the construction of an energy-saving and efficient integrated transportation system, focus on the development of the electric vehicle industry, and strengthen the construction of charging and swapping infrastructure and smart car networking platforms.

5.2.3 Promoting scientific and technological innovation and the overall planning of research, demonstration, and industrialization of key technologies

The path design of power system emissions reduction should fully consider the foresight of technology breakthroughs, strengthen the guidance of science and technology strategies, and formulate the science and technology development plan of the new power system. We should continue to strengthen R&D and demonstration projects of key technologies related to carbon neutrality and re-electrification, amplify the supporting policy system, and provide incentives for industrialization. Moreover, we should deploy major technological R&D in advance, strive to achieve breakthroughs in disruptive technologies, and catalyze commercial applications. We should promote technological progress in the whole process of low-carbon clean energy production, distribution, circulation, and consumption. The maturity of key technologies such as high-efficiency and low-cost energy storage, CCUS, hydrogen energy, and high-efficiency electric equipment will have a profound impact on the promotion of re-electrification and the realization of carbon neutrality goals, so they should be laid out in advance and commercialized as soon as possible.

5.2.4 Improving power and carbon markets

We should formulate a top-level design scheme and implementation roadmap for the national unified power market, research and issue relevant policies based on power generation and consumption fields, release the power generation and consumption plan, expand market scope, and fully stimulate the potential of new energy accommodation on both sides of power generation and consumption, forming a healthy accommodation pattern with source–load–interaction. Additionally, we should optimize and combine excess renewable energy accommodation and voluntary green certificate subscriptions and develop a single green consumption certification system based on green power transactions. We should coordinate and connect relevant policies such as accommodation responsibility, carbon quotas, and carbon taxes to promote goal and mechanism coordination among the carbon, green power, and green certificate markets to form synergies in a common direction. Furthermore, we should actively introducing green finance development support policies, which would internalize the environmental costs of enterprises or projects through policy implementation, improve the role of market mechanisms in green finance, and stimulate the vitality and enthusiasm of relevant industries to participate in green credit.

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