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Study of the Situation and Direction of China's Energy Technology Revolution

Rao Hong [1], Li Licheng [2], Guo Xiaobin [1], Xu Aidong [1], Bai Hao [1]

1. Electric Power Research Institute, CSG, Guangzhou, 510663, China
2. China Southern Power Grid Co., Ltd., Guangzhou, 510663, China

Abstract: The energy technology revolution is the basis for boosting the energy consumption, supply, and institutional revolutions, and strengthening international cooperation. The energy technology revolution supports a modern, clean, low-carbon, safe, and efficient energy system. It is an important part of building an innovation-oriented country. In this paper, the energy situation and challenges in China are discussed; future energy structures in three-time nodes, including 2020, 2030, and 2050, are studied; and common trends of technology development to realize the collaboration of multi-field energy technologies are summarized. In addition, the directions of energy technology developments to realize the leapfrog development and to build an energy technology innovation system with Chinese characteristics are discussed.

Keywords: energy technology revolution; energy situation; energy structure; technology trend; technical direction

1 Introduction

On June 13, 2014, Xi Jinping hosted the 6th meeting of the Central Financial and Economic Affairs Commission to address the changes that are taking place in the energy supply and demand patterns of China and global energy development trends. During this meeting, the "Four Revolution, One Cooperation" strategy was put forward to safeguard the energy security and development needs of China. An energy technology revolution was proposed for the first time, which exemplifies the importance of energy technology innovations for the overall development of China's energy sector. The energy technology revolution will transform the energy consumption, energy supply, and energy systems in China and enable the establishment of a green, low-carbon, safe, efficient, sustainable, and modern energy system during the 13th Five-Year Plan. The energy technology revolution is therefore an important part of China's efforts to establish itself as an innovation-oriented country [1].

A new round of energy technology revolution has already started to emerge, representing a historic opportunity that must be seized by China. Therefore, it is necessary to accurately analyze China's energy situation and endowments to provide a clear outlook on China's energy consumption structure in 2020, 2030, and 2050. A direction for China's energy technology revolution must be proposed based on the technology trends with respect to nuclear power, wind power, solar power, energy storage, oil and gas, coal, hydropower, biomass energy, and smart grid to support China's energy structure transformation and seize a commanding position in the energy revolution. This will allow China to lead and define this new round of energy technology competition and thus dominate the global economic–political sphere and energy systems of the future.

2 China's energy situation

China has become the world's largest energy producer and consumer. Comprehensive energy supply systems based on coal, electricity, oil, natural gas, and new and renewable energy sourc-

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Corresponding author: Xu Aidong, Electric Power Research Institute, CSG, Senior Engineer. Major research fields include electric power system analysis and control, smart grid, and information communications. E-mail: xuad@csg.cn
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es have been established. Furthermore, significant improvements have been realized with respect to the technological level, energy production, and living standards of China. The achievements of the Chinese energy sector have attracted worldwide attention. Although the energy supply–demand problems of China have subsided to some extent, structural and institutional conflicts have become major obstacles with respect to the sustainable development of China's energy sector. Furthermore, China's energy development faces numerous complexities and risks, which severely challenges its sustainable development.

2.1 Heterogeneities in the geographical distribution of energy resources

China's coal resources are mainly located in northern and northwestern China. The geological conditions of these resources are immensely challenging. Only a very small amount of these resources is accessible via open pit mining. The oil and gas resources of China are mainly located in eastern, central, and western China and China's marine areas. These resources also occur in geologically complex regions, at great burial depths, which impose high demands on oil and gas exploration technology. China's undeveloped hydropower reserves are mainly located in the high mountains and deep valleys of southwestern China, which makes the development of these resources very challenging and costly. The most important energy consumption zones of China are at the highly developed coasts of southeastern China. The energy situation of China is thus characterized by long-distance energy transport on a gigantic scale; coal and oil are transported from northern to southern China, while gas and electricity are transported from western to eastern China.

2.2 Severe problems of primary energy consumption structures of China

Coal, oil, natural gas, and non-fossil fuel sources accounted for 61.93%, 18.83%, 6.28%, and 12.96% of the primary energy consumption structure of China in 2016. Hence, the energy utilization in China is highly monotonous and overly reliant on fossil fuels such as coal and oil. This is consistent with the current state of China's energy resources and shows that the energy structures of China are poorly balanced. Therefore, China is susceptible to economic risks and energy problems that may arise from future coal and oil shortages. Hence, significant efforts must be made with respect to the development of non-fossil energy sources, such as nuclear, hydro-, wind, and solar power, to meet the growing energy demand of China.

2.3 Safeguards are required to secure and sustain the development of China's energy supplies

The oil import dependency is an important metric for the assessment of the security of a country's or region's oil supplies. Because of decreases in the domestic oil production and increases in oil imports, the oil import dependency of China rose to 65.4% in 2016. This level of reliance renders China susceptible to external factors such as supply outages and oil price fluctuations. Because the Asia–Pacific region is connected to Central Asia and important maritime routes, the primary energy-related geopolitical challenges of China include the control of shipping routes, competition for overseas resources, and competition for offshore oil and gas resources. More than 80% of China's oil imports must pass through the Indian Ocean and Malaccan Straits; the Malaccan straits are especially susceptible to external interference, which threatens the passage of energy shipments. Therefore, China must actively establish new resource channels such as the Sino–Myanmar pipelines and Kra Isthmus canal. Resource trading with Russia and Central Asia should be strengthened through the "One Belt One Road" project to expand China's energy import sources.

2.4 Environmental consequences of energy development are becoming increasingly severe

China's coal-dominated energy consumption structure has caused severe environmental pollution, which is further compounded by low-efficiency coal combustion and the lack of pollution management measures. The combination of these issues has led to frequent smog incidents. The tremendous coal consumption levels of China and the innate carbon intensity of coal have caused coal-related CO_2 emissions to become the main CO_2 emissions from China. These emissions have also made China the largest carbon emitter in the world. In some parts of China, the environmental capacity for energy production and consumption is approaching its upper limits and the air pollution in these areas is extremely severe. Cleaner coal substitutes, such as gas and electricity, are expensive and the propagation of cleaner coal varieties has been beset by difficulties. Large amounts of coal are being utilized in a dispersed manner, that is in small stoves/furnaces and in household applications, which emit large amounts of pollutants. Furthermore, the use of cleaner high-quality oil products is low and there is an urgency to improve the quality of motor fuels. Because of the increase of nuclear power developments, the amount of spent fuel that is being removed from nuclear power plants in China is continuously increasing. There are significant weaknesses in China's capabilities to process spent fuel and the pressure based on the lack of effective measures to handle spent fuel storage and disposal is growing each day.

2.5 China's low comprehensive energy utilization rate

The World Bank's data showed that the energy per unit of GDP (energy intensity) of China in 2016 was 3.7 tons of coal equivalent (tce)/10 000 USD, which is 1.4 times the average energy intensity of the world and 2.1 times the average energy intensity of developed nations. The comprehensive energy utilization rate of China is therefore much lower than that of developed nations. The comprehensive energy utilization rate refers to the ratio between the actual output energy and the effective energy received by energy mining/extraction, processing, conversion, storage/transfer, and usage processes. This includes the efficiency of energy production and other intermediary processes as well as the end use energy efficiency. The efficiency of coal–power conversion during energy production still has room for improvement. The gap between electricity and natural gas peaks during energy transmission is steadily growing and the ability of China's energy systems to regulate peak loads is inadequate. Furthermore, peak load regulation during large-scale long-distance power transmission requires large amounts of coal power; clean energy only makes up a small proportion of the power being transferred by China's energy systems. In some regions, the wind, hydro-, and solar power curtailment is extremely severe and system utilization rates are low. The integration of electricity, heating, and gas supply systems in energy end use is poor, which prevents complementary and cascading energy use. Demand side response mechanisms have yet to be fully established and the design of the supply capacity is always based on the maximum load, which led to the continuous decline in capacity utilization rates.

2.6 Long-term technology roadmaps and technology systems have yet to be defined for each area of the energy sector

Although rapid development has been achieved in nuclear power, wind power, solar power, energy storage, oil and gas, coal, hydropower, biomass power, and smart grid technologies, China still relies on imports of some of the key equipment for these industries. The reliance of large energy projects on imported equipment is common. Satisfactory solutions for problems, such as "technology hollowing" and China's reliance on imported technologies, have yet to be found. In addition, China's innovation models need to be upgraded. Although the technology transfer has provided fruitful results, there is still a lack of original innovations that cater to China's specific needs. In the absence of a clearly defined technology system for each part of the energy sector, it is impossible to identify the most important technical areas and their corresponding key technologies. This results in the dispersion of technical capacity and an inability to concentrate manpower, material, and financial resources to solve important technical problems, which slows down the development of core technologies. Although research roadmaps have been formulated by relevant research institutes, long-term technology roadmaps have yet to be established. This results in redundant studies and difficulties in the coordination and planning of research efforts to drive technological advancement. Furthermore, it is impossible to improve the technology in a steady manner via the interconnection of technology nodes without the establishment of well-defined development milestones and evolutionary relationships between each technology. Hence, the formulation of a well-defined technology roadmap and technology system will allow large enterprises and research institutes to determine the directions and focus areas of their development based on careful consideration of their own circumstances and market research.

3 Outlook on China's energy consumption structures

In the report of the 19th National Congress of the Communist Party of China, it was noted that a clean, low-carbon, safe, and efficient energy system must be constructed to form an energy structure that is simultaneously driven by coal, oil, gas, nuclear power, new energy sources, and renewable energies. An energy technology revolution is indispensable for this new energy structure. In the following sections, the paper analyzes the energy consumption structures of China in 2020, 2030, and 2050 based on currently foreseeable trends and the current state of China's policies. This work provides a reference for the formulation of China's energy technology roadmaps and systems.

3.1 Current state of the Chinese energy sector

Based on Figs. 1 and 2, the energy consumption structure of China is transitioning towards clean energy. The total primary energy consumption of China in 2016 was 4.36×10^9 tce, which is 1.4% higher than that of the previous year. Based on this number, China is the largest energy consumer in the world. Fossil fuels accounted for 87.11% of the energy consumption. The consumption of coal was 2.7×10^9 tce, which is 4.7% lower on a year-on-year base; its proportion in the energy mix was 61.93%, which is 2% lower than that of the previous year. The consumption of oil was 8.21×10^8 tce, which is 5.5% higher on a year-on-year base; its proportion in the energy mix was 18.83%. The consumption of natural gas was 2.74×10^8 tce, which is 8.0% higher than that of the previous year, and its proportion in the energy mix was 6.28%. The total electricity consumption of China was 5.9198×10^{12} kW·h, which is 5.0% higher on a year-on-year base. Non-fossil energy sources, such as hydro-, wind, and nuclear power, accounted for 12.96% of the energy mix, that is, 1.3% higher on a year-on-year base.

3.2 Outlook on the energy mix of China in 2020

China's energy structure will be optimized between 2016 and 2020. During this period, China must focus on the development of clean, low-carbon energy sources to adjust its energy structure and continue to develop non-fossil energy sources alongside clean and efficient fossil fuel utilization. The simul-

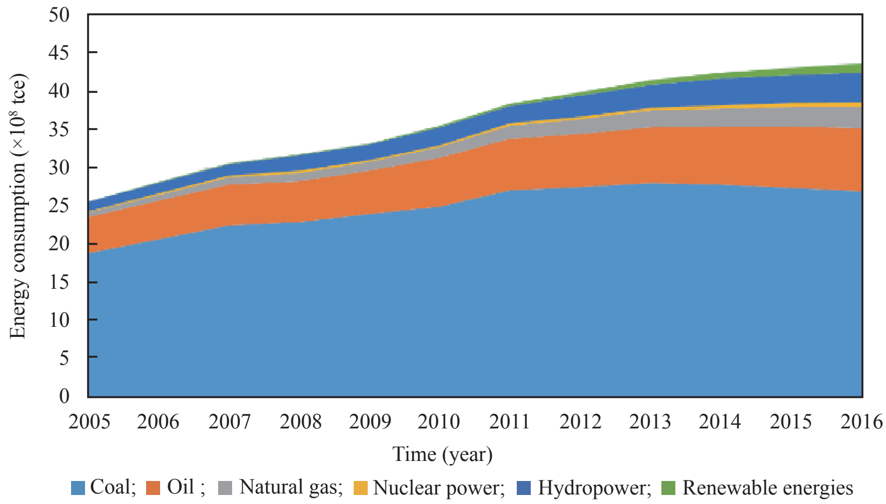

Fig. 1. Trends of the energy consumption structure of China from 2005 to 2016.

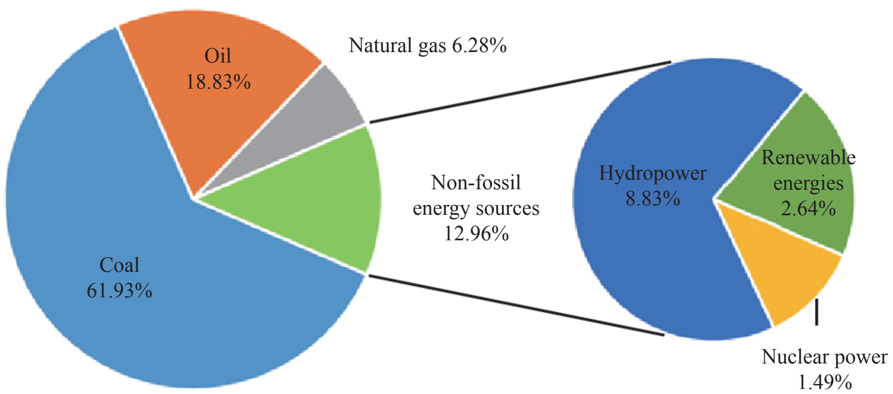

Fig. 2. Primary energy consumption structure of China in 2016.

taneous development of non-coal power generation and clean and efficient coal power should be continued to gradually reduce the proportion of coal in the energy mix. The proportion of non-fossil energy sources and natural gas in the energy mix should be increased. In addition, the replacement of coal with oil/gas and fossil fuels with non-fossil energy sources should be accelerated [2–5].

By 2020, the total energy consumption of China should range between 4.7×10^9 tce and 4.9×10^9 tce. The ratio between coal, oil/gas, and non-fossil energy sources will be approximately 6:2.5:1.5. The total consumption of coal will be restricted to 4.1×10^9 t and its proportion in the energy mix will be reduced to 58%; coal consumption will thus be peaking (Fig. 3). The total consumption of oil will be 5.9×10^8 t, which increases its proportion to 17%. The proportion of natural gas will steadily rise to 10%, that is, 4.1×10^{11} m^3. The proportion of non-fossil energy sources will increase to 15% or more and the utilization of nuclear, hydro-, wind, and solar power and biomass energy will reach 1.7×10^8 tce, 3.7×10^8 tce, 1.5×10^8 tce, 1.4×10^8 tce, and 6×10^7 tce [6], respectively.

3.3 Outlook on the energy mix of China in 2030

The transformation of China's energy structure will take place between 2021 and 2030. During this period, the energy consumption structure of China will significantly improve and green, low-carbon developments in the energy sector will become a reality. Hopes are that the ratio between coal, oil/gas, and non-fossil energy sources in the energy mix will reach 5:3:2 by 2030. The proportion of non-fossil energy sources will increase to 22% and break China's absolute reliance on fossil fuels. The proportion of wind, hydro-, and nuclear power in the energy mix is expected to increase [7–10]. The fossil fuel-based energy structure of China will evolve from a coal-dominated structure into a more rational mixture of coal, gas, and oil, thus becoming less carbon-intensive and cleaner.

The increase in the total energy consumption of China will somewhat slow down during 2020–2030 and reach 5.3×10^9 tce in 2030. The primary energy mix of China will continue to improve and the proportion of conventional fossil fuels in the energy mix will decrease to 78% (Fig. 4). Because the coal

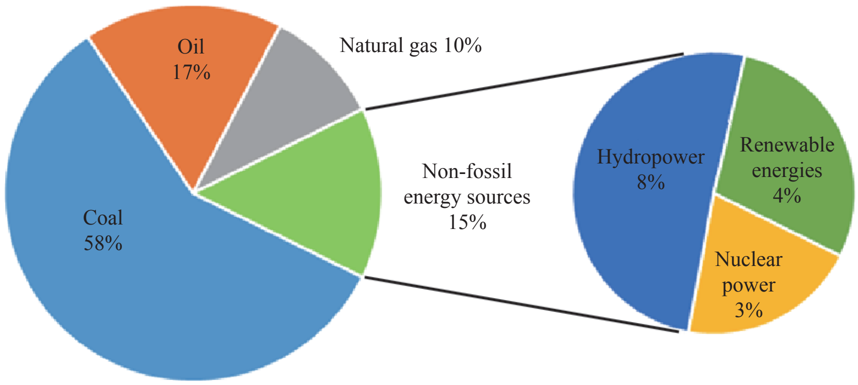

Fig. 3. Outlook on the energy mix of China in 2020.

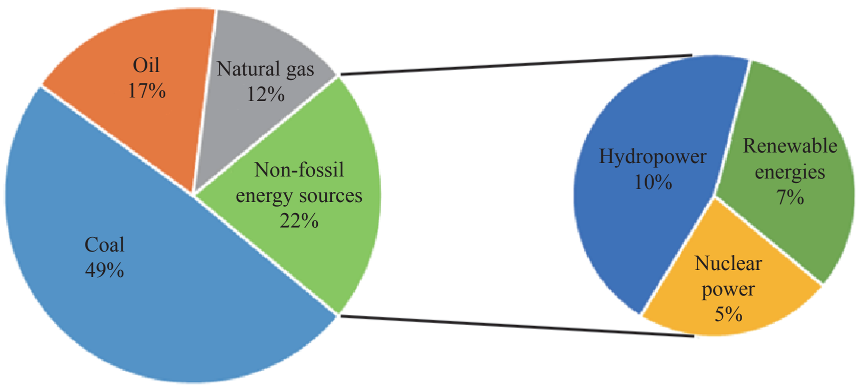

Fig. 4. Outlook on the energy mix of China in 2030.

consumption has already peaked, the coal consumption will decrease to ~3.6×10^9 tce and its proportion will decrease to 49%. The oil supply/demand in China will grow at a rate of 1%–2% per year from 2020–2030. By 2030, the oil consumption will reach 6.5×10^8 t and its proportion in the energy mix will remain at 17%. The annual growth of the natural gas supply/demand in China will decrease to ~5%. The natural gas consumption of China will be 4.1×10^{11} m^3 in 2030 and its proportion will reach 12% [11,12]. The proportion of oil will decrease, while the proportion of natural gas will increase, thus rationalizing the oil–gas ratio to approximately 1:0.7 in 2030. The proportion of non-fossil energy sources will increase to approximately 22% and the proportion of nuclear, hydro-, and renewable energy sources in the energy mix will be 5%, 10%, and 7%, respectively.

3.4 Outlook on the energy mix of China in 2050

The energy revolution will take shape during the 2030–2050 period and lead to the formation of a new energy system. Based on energy supply reforms, the energy consumption will peak around 2035 and reach 5.5×10^9 tce. The total energy consumption of China will contract at a rate of 0. 4% and 0. 5% per annum between 2030 and 2040 and between 2040 and 2050, respectively; the total primary energy consumption of China will decrease to 5×10^9 tce by 2050 [7,8]. By maximizing the utilization of renewable energies, the expectations of the *Energy Production and Consumption Strategy* for 2050 will be realized, that is, non-fossil energy sources will account for more than 50% of the energy mix in 2050.

The slowdown of China's economic growth, improvements to its energy structure, and high levels of public awareness for environmental pollution and climate change will drive earlier-than-expected decreases in the coal consumption. Because of China's stringent coal control policies, China's coal consumption will decrease to 1.86×10^9 tce by 2050, which represents an average annual decrease of 1%. Because of the slowdown of the economic growth and the formulation of environmental policies, the growth of coal power will be restricted, while the efficiency of coal power generation will increase. It is expected that the coal power generation will continuously decrease starting in 2030. At this point, the increase in China's power demands will be met by renewable energies and nuclear power. The consumption of refined oil products will rapidly decrease after 2035 due to continuous improvements in the fuel economy and the popularization of alternative fuels and electric cars. The oil consumption will decrease to approximately 5×10^8 t by 2050. The demand for natural gas will continuously grow from 2016–2050, at a rate of approximately 3.8% per year. By 2050, the natural gas consumption will reach 7×10^{11} m^3, which is close to the current consumption level of the U.S. The net natural gas imports will reach 2.85×10^{11} m^3 in 2050, which corresponds to an import dependence of 40% [13].

The fossil fuel consumption in China will peak by 2030 and decrease on average by 2.3% per annum from 2030 to 2050. In addition, the proportion of fossil fuels in the energy mix will decrease to 49% by 2050. The proportion of coal in the energy mix will continuously decrease and reach 26% by 2050 [14,15], as shown in Fig. 5. The rapid development of electric power replacement technologies will lead to a rapid decrease in the oil consumption and the proportion of oil in the energy mix will decrease to 9% by 2050. The proportion of natural gas consumption will increase to ~14%. The consumption of non-fossil energy sources will grow much faster than that of fossil fuels. By 2050, the consumption of non-fossil energy sources will reach 1.54×10^9 tce (more than 50% of the energy mix), which represents an average annual growth of 1.3% from 2016–2050. In particular, renewable energies, such as solar and wind power, will show the most rapid growth. The proportion of renewable energies in the energy mix will increase from 7% in 2030 to 26% in 2050.

4 Technology development trends

The development trends and technology roadmaps regarding nuclear power, wind power, solar power, energy storage, oil and gas, coal, hydropower, biomass energy, and smart grid-energy network integration are not the same, but certain parts of their development overlap. In summary, different energy technology developments generally exhibit common foundations and crosslinks, permeation and fusion, advanced and high-end technologies, as well as intelligence and efficiency. Technological breakthroughs and innovations in basic research, technological research and development, and engineering demonstrations should be prioritized. In addition, meaningful collaborations should be established between research, design, manufacturing, experimentation, and operations to enable their mutual improvement.

4.1 The same intrinsic drivers are shared by different areas of the energy sector

Improvements and breakthroughs in energy technologies increasingly rely on the development of innovative technologies in basic sciences such as materials science, advanced manufacturing, and information and communications technology. Different types of energy will, by necessity, develop in different directions. However, the theories, components, and materials used by different areas of the energy sector often share the same foundations and intrinsic drivers. Therefore, a breakthrough in a fundamental area of science could lead to leapfrog development in many energy technologies. Future energy technology developments will place increased emphasis on the crossings of energy and non-energy related technologies, especially in basic theoretical research on energy, materials, environmental science, information technology, and data science. For example, the development of high-temperature materials is crucial to increase the technological level of the equipment used in nuclear and oil, gas, and coal-based power generation because they enhance the energy use and power generation efficiency. Nanotechnology is an important technology for solar power and oil/gas exploration. Advanced sensor technologies play an important role in oil and gas exploration, intelligent wind farm monitoring and management, hydrological forecasts, and smart grid–energy network integration. Advanced power electronic conversion technologies are core technologies for wind power, solar power, energy storage, and smart grid–energy network integration and their scope of applications in the energy sector is extremely wide. It should also be noted that high-voltage high-current power semiconductors and wide bandgap semiconductors are of fundamental importance for the development of power electronic conversion technologies.

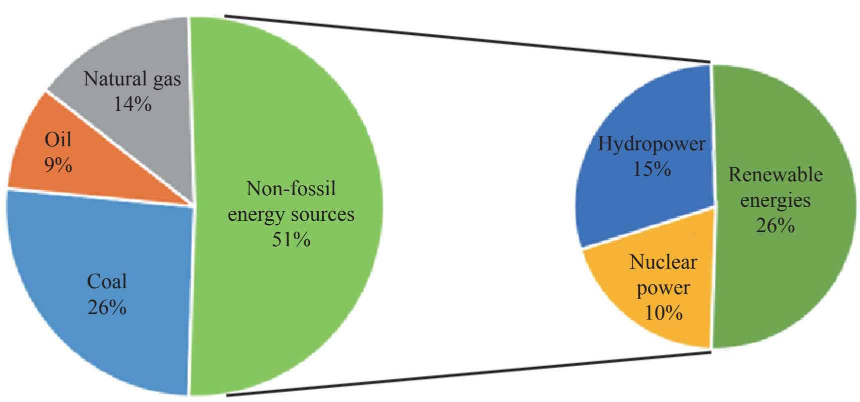

Fig. 5. Outlook on the energy mix of China in 2050.

4.2 Fusion of different areas of the energy sector

The fusion of different areas of the energy sector occurs at physical and information levels in energy production, transmission, and consumption. The goal of this integration is to strongly couple information and energy flows between different types of energy. Future energy technology developments will trend towards the construction of safe, low-carbon, clean, and efficient next-generation integrated energy systems based on the holistic progress of each type of energy technology. This does not merely pertain to technology improvements in some energy-related process because it requires the involvement of all processes (production, supply, and consumption) in every area of the energy sector. The aim of integrated energy systems is to overcome the barriers related to uncoordinated energy plans, industry fragmentation, and industry monopolies to provide reliable energy networks and advanced equipment for the production, transmission, usage, storage, and conversion of primary and secondary energies. The energy system revolution and infiltration of internet technologies has provided new opportunities for technology fusion and innovations in the energy sector. For example, excellent prospects are available for the combination of solar thermal power plants with other forms of energy such as cascade solar–gas, solar–biomass, solar–wind, and solar–coal power plants. Natural gas systems can be combined with electric power systems on the load side through combined heat and power (CHP) generation or combined cooling, heating, and power (CCHP) generation, while power–gas technology can be implemented at the source end of the grid side to optimize the operation of multi-energy supply systems. Heating systems can be combined with electric power systems via power–heat coupling and energy storage technologies in receiving-end systems. Coupling devices imbue interconnected energy systems with greater levels of flexibility and reliability and are beneficial for the local consumption of distributed renewable energies. Information and communications technology are necessary for efficient information communication and sharing between energy systems and processes of next-generation integrated energy systems. These technologies enable real-time data collection from all energy-related processes and the coordination of multiple energy production systems, multi-energy dispatching, and energy trading services.

4.3 Energy-related technologies are generally highly advanced

The components, equipment, systems, and processes/integration involved in energy production, transmission, usage, storage, and conversion are in general very technologically advanced. More specifically, these technologies exhibit excellent performances, high volumes/densities, high safety factors, and high levels of integration. The main purpose of these technologies is to increase energy utilization rates and decrease the cost of energy utilization and integration. For example, the next step of technological development in nuclear power is the advent of fast reactors capable of uranium utilization rates of ≥60%. The development of high-altitude and offshore wind power will require breakthroughs in the key components and technologies of high-reliability 10 MW offshore wind turbines including super-sized 100 m lightweight wind turbine blades and wind turbine converters. In the field of solar power utilization, photoconversion efficiencies of ≥25% need to be achieved in monocrystalline solar cells and it is also necessary to develop the core processes, equipment, and technologies required to produce long-life (35 years) low-degradation crystalline solar cells. In the field of energy storage, the construction of 10 MW/100 MWh and 100 MW/800 MWh supercritical compressed air energy storage systems will require technological breakthroughs with respect to wide-load compressors, multi-stage high-load turboexpanders, and compact thermal energy storage heating (cooling) exchangers in terms of flow, structure, and strength. It is also important for the energy density of Li–S batteries to reach 300 Wh/kg and the cycle life of lead-carbon batteries to exceed 5 000 cycles. Because China’s oil and gas development is trending towards deep seas and deep wells, wide azimuth multi-component high-resolution seismic exploration technologies must be capable to achieve a resolution <3 m at a depth of 4 500 m in eastern China, a resolution <7 m at a depth of 7 000 m in western China, and a fault throw resolution below 5 m. In addition, 700°C ultra-supercritical coal combustion technology is necessary for clean and efficient coal usage. Therefore, the materials and components needed for 700°C steam power plants need to be developed and schemes and techniques for the design of 600 MW 700°C ultra-supercritical power generation systems need to be acquired. Because hydropower developments involve increasingly high hydraulic heads, there is a need to develop $>4 \times 10^5$ kV impulse turbine hydropower plants that can handle a hydraulic head of 700 m. Because the development of direct-current (DC) power transmission lines is trending towards higher voltages, it will be important to achieve breakthroughs with respect to key technologies related to ±1100 kV ultra-high voltage direct-current (UHV DC) power transmission and <500 kV voltage source converter-based direct-current (VSC DC) power transmission via overhead power lines.

4.4 Smart technologies will profoundly change the energy sector

The establishment of an intelligent technology system based on advanced sensors, information and communications technologies, control technologies, Internet technologies, cloud computing, big data technologies and artificial intelligence will lead to profound changes in all conventional energy industries and their industry chains. Such a system will enable omniscient sensing, digitalized management, intelligent decision-making, and automated operations and maintenance in all energy-related processes including energy production, transmission, usage, storage, and conversion. After achieving the physical integration and smartization of the energy systems, Internet technologies can be used to further enhance the intersystem integration at the information level, thus "smartizing" the integrated energy system. A common service network may then be constructed to monitor, manage, and schedule energy production operations, which will drive the revolutionization of energy production and consumption, further enhance the energy utilization efficiency, and enable the full consumption of renewable energies. For example, conventional technology systems used in oil and gas exploration will transform into intelligent technology systems based on nanoscale micro-/nanotechnologies, smart materials, artificial intelligence, and quantum technology. A next-generation intelligent technology system for oil and gas exploration based on disruptive technologies, such as intelligent and accurate directional drilling and completion systems, nanoscale oil extraction, and *in situ* modification for enhanced oil recovery, is already starting to take shape. In the area of smart nuclear power technologies, uranium utilization improvement technologies, online monitoring and smart diagnosis could reduce the need for spare parts and thus improve the operational efficiency. In the future, supercomputers will be used to refine the analysis of nuclear power plant designs and to perform multi-physics simulations of these designs. In the area of power generation equipment, Internet technologies, big data, and cloud computing will be used to develop design, control, intelligent operations/maintenance, and fault diagnosis technologies that cover the life cycle of the equipment. High levels of smartization will be achieved in integrated energy systems (including the power grid), thus forming an energy transmission network with zero marginal costs and the Ubiquitous Energy Network. This network will facilitate the intelligent, reliable, and optimal acquisition of energy, in any form, and prioritize the transmission and consumption of renewable energies. The fusion of data from the integrated energy system via Internet technologies will lead to business model innovations and new industry chains for the energy sector.

5 Direction of the energy technology revolution

A new round of technological and industrial revolution is currently emerging, which has triggered a new wave of technological innovations around the world. Novel energy technologies are replacing conventional energy technologies at an unprecedented pace, thus transforming the global energy situation. China must keep pace with the transformation of the energy sector by conceiving new development strategies and focus its efforts on breakthrough technological bottlenecks to spur its own energy technology revolution and a major revolution in China's energy production and consumption modes. China's energy technology revolution must be conducted in a scientific, holistic, and strategic manner. In other words, it is necessary to bear current realities in mind while keeping an eye on long-term developments to provide the technological support necessary for the establishment of a safe, green, low-carbon, cost efficient, sustainable, and modern energy industry system.

5.1 Innovative technologies are developed to achieve independent energy technology innovation

Innovative technologies are the core impetus of the energy technology revolution. China's energy sector is lacking certain core technologies, which has led to an increased import reliance with respect to key equipment and materials. For a long time, the development of key technologies in areas such as Generation III nuclear power plants, new energy sources, and shale gas have relied on technology transfer. Furthermore, significant gaps have always been present in gas turbine, high-temperature material, and off-shore oil and gas exploration technologies. The development of energy technologies in China has always been focused on closing the gap between China and other advanced nations and on reversing this gap. However, it has been repeatedly proven that it is impossible to simply import a key technology. Independent innovation is the only way to gain a secure foothold in these technologies. The development of innovative technologies should be sustained to take the global lead in energy technologies, eliminate the reliance on external imports, and achieve technological independence with respect to energy technologies. This will satisfy the short-term energy technology needs of China and assist the transformation of energy developments in the future.

In the near term (before 2020), the focus of the energy technology revolution will be research and independent creation of innovative technologies in each area of the energy sector. Original innovations, integrated innovations, and technology transfer will be strengthened during this period. The priority areas for nuclear power are the optimization of Generation III nuclear power technologies and the development of generalizable products to drive the coordinated development of the nuclear power industry's chains. The priority areas for renewable energies and energy storage are: (1) intelligent manufacturing and operations/maintenance technologies for onshore wind turbines, (2) manufacturing technologies for the key components of high-efficiency photovoltaic arrays and high-capacity energy storage systems, (3) technologies for the construction of hydropower plants under complex geological conditions, and (4) the piloting of large-scale biofuel production technologies. The focus areas of the energy-savings industry are advanced energy-savings standards, testing, certification, and evaluation techniques. The priority areas for fossil fuel-based energy technologies are the development of micro-/nanoelectromechanical systems and smart materials for oil and gas applications. The focus areas of smart grid-energy network integration are hybrid alternating-current/direct-current (AC/DC) power transmission and smart grid-based energy supply technologies.

5.2 Forward-looking technologies are deployed to reach an internationally advanced level

Forward-looking technologies will serve as the cornerstone of the energy technology revolution and drive its advancement. History has shown that if a country lacks foresight in basic energy research, it will be difficult for this country to catch up to other advanced nations because its technological level will always lag behind the latter. Amidst the global energy technology revolution and industry transformation, China must adopt a forward-looking strategic outlook, study the deployment of advanced energy technology systems, and persevere in the development of forward-looking technologies. This is necessary for China to catch up to other advanced nations in a timely manner and to drive the advancement of its energy technology revolution to achieve a holistic upgrade of its energy structure.

In the medium term (before 2030), the energy technology revolution will focus on bolstering the deployment of potential technological directions in each area of the energy sector, scientifically analyzing the viability and technological potential of each technology, and promoting industry–university research collaborations. This will steadily close the gap between China and other advanced nations; China will take the lead in certain areas based on technological breakthroughs. The priority areas for nuclear power are: (1) Breakthroughs in nuclear power safety technologies, such as accident-tolerant fuels, to eliminate large-scale radioactive matter releases in a comprehensive manner and improve the competitiveness of the nuclear power industry; (2) The realization of closed fuel cycle pressurized water reactors alongside the coordinated development of nuclear power industry chains; (3) The maturation of Generation IV reactors, such as sodium-cooled fast reactors, and breakthroughs in key technologies such as nuclear fuel breeding and the transmutation of high-level radioactive waste; and (4) Active research about multipurpose applications for small modular reactors. The priority areas for renewable energies and energy storage are: (1) Intelligent manufacturing and operations/maintenance technologies for 10 MW offshore wind turbines, (2) High-performance solar–thermal power generation technologies, (3) Technologies for the design of high-efficiency energy storage structures and material development, (4) The design of small environmentally friendly hydroelectric dams and high-head hydropower plants and water turbine manufacturing technologies, and (5) Power generation via biomass cofiring and gasification. The energy-savings industry should focus on the development of an advanced energy technology system with independent intellectual property rights. The focus areas for fossil fuel-based energy technologies are: (1) Deep oil/gas reservoir development technologies and technologies for the exploitation of special-quality oil and gas resources, and (2) Advanced coal gasification technologies for different coal ranks. The focus areas of smart grid-energy network integration are technologies for the construction of integrated energy networks and transparent power grids.

5.3 Disruptive technologies are developed to lead the world in energy technologies

Disruptive technologies represent the transformative power of the energy technology revolution. The study and development of disruptive technologies is of profound significance for China's ambitions to lead the world in all energy-related areas, key industries, and mainstream products. Disruptive technologies will disrupt conventional technology roadmaps and leapfrog the development of incremental technologies. To realize these technologies, a breakthrough from current modes of thought and the "gradual to sudden" vertical development model must be achieved. The boundaries of each discipline must be surmounted; cross-disciplinary studies that enable the mixing and crossing of different disciplines and research directions must be embarked upon. This includes the application of quantum computing, graphene materials, superconductors, and Internet technologies in the petrochemical industry, energy storage, new energy sources, and power systems.

In the long term (before 2050), the direction of the energy technology revolution is to identify, capture, and nurture disruptive technologies that will have a strategic impact on the energy supply security and to conduct research in these areas in a scientific and systematic manner. China will thus capture the strategic initiative of the energy technology revolution and solidify its dominance in the global energy technology competition. The focus areas of nuclear power are the realization of closed fuel cycle fast reactors, co-development of pressurized water reactors and fast reactors, and construction of a nuclear fusion demonstration project. The focus areas of renewable energies and energy storage are: (1) Novel wind power utilization technologies such as high-altitude wind power and their equipment, (2) Novel high-efficiency solar cell technologies, (3) Hydrogen energy storage and multifunctional hybrid energy storage technologies, (4) Technologies that combine intelligent watershed management with intelligent hydropower plant design, intelligent water turbine manufacturing, and intelligent hydropower generation, and (5) The commercialization of new high-quality energy plant species. The energy-savings industry should prioritize the integration of advanced energy-savings technologies with next-generation information technologies. The focus areas for fossil fuel-based energy technologies are: (1) Extreme oil drilling and intelligent oil recovery technologies, (2) Novel coal-based power generation technologies, and (3) Magnetohydrodynamic combined-cycle power generation. The focus areas of smart grid-energy network integration are electronic switches based on functional materials and the establishment of the Ubiquitous Energy Network..

6 Conclusion

The transformation of China's energy structures will require the support of novel energy technologies and sustained research efforts with respect to fundamental technologies of all energy-related areas. This will drive the interconnection and integration between different areas of the energy sector and promote the advancement and smartization of China's energy technologies. China must persevere in the development of innovative, forward-looking, and disruptive technologies to support the optimization, transformation, and shaping of China's energy structure. These efforts will increase the proportion of non-fossil fuels in China's energy mix to 15%, 22%, and 51% by 2020, 2030, and 2050, respectively, and lead to the gradual establishment of a clean, low-carbon, safe, and efficient energy system, thus bringing China's energy technology strategy to fruition.

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