DOI 10.15302/J-SSCAE-2018.03.001

Strategic Research on China Energy Technology Revolution System

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

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

Abstract: In 2015, to promote an energy technology revolution, the Chinese Academy of Engineering launched a major consultation project called Strategic Research on China Energy Technology Revolution System. This paper outlines a development strategy through consultation and investigation in nine key energy areas, including nuclear energy, wind energy, solar energy, energy storage, oil and gas, coal, water energy, biomass energy, and integration of the smart grid and energy network. Based on the systematic analysis of China's current situation of energy technologies, this study proposes an energy technology system in which renewable energies represent the main part, electric energy is the main end-use energy, and multiple energies and grids integrate and complement each other. Furthermore, the study develops an energy technology route including three stages for development of forward-looking (2020), innovative (2030), and disruptive (2050) technologies. Finally, a strategy providing scientific support for making plans and policies about energy in China to promote the energy technology revolution is proposed.
Keywords: energy technology revolution; energy technology system; energy technology route; strategic research; strategy proposal

1 Introduction

Energy supply and consumption are undergoing profound changes on a global scale, as the mitigation of global climate change requires a progressive reduction of the reliance of mankind on conventional fossilized fuels. This has led to the rapid development of new energy sources and renewables, and the advent of "energy saving, emission reducing, and low carbon" development trends in energy supply. In the face of the changing energy supply landscape and international energy development trends [1], China must revolutionize its energy technologies, promote the diversification of energy supply modes, improve the integration and efficiency of energy usage, and refine energy consumption systems in a scientific manner.

During the 19th National Congress of the Communist Party of China, it was noted that socialism with Chinese characteristics had entered a new era characterized by the contradiction between unbalanced and inadequate development and people's needs for a better life. It was also noted that energy consumption deeply influences the socioeconomic development of China, as it is deeply interconnected with the Chinese society and economy. At present, the transformation of energy supply systems in China is urgently required to transform China's economic structures and implement climate governance. Therefore, China's capacity for independent innovation must be strengthened. The research and application of new technologies must be vigorously pursued to promote the transformation of energy structures and efficient energy usage as well as to satisfy the people's ever-growing needs for a better life. However, the energy sector is closely interconnected with many other sectors, requires large investments, operates on long timescales, and has high levels of inertia, which highlights the need to identify clear directions and associated milestones required to achieve comprehensive, coordinated, and sustainable development. This will facilitate the establishment of

Received date: June 5, 2018; **Revised date:** June 12, 2018
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
Funding program: CAE Advisory Project "Strategic Research on the Technological Trend and System of the Energy Technology Revolution in China" (2015-ZD-09)
Chinese version: Strategic Study of CAE 2018, 20 (3): 001–008
Cited item: Li Licheng et al. Strategic Research on China Energy Technology Revolution System. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2018.03.001

an energy technological system in-line with cutting-edge technologies of the world and China's resources and requirements.

2 The current state of energy technologies in China

Based on in-depth research and analysis, we found that the technological level of China in nuclear energy, solar energy, energy storage, oil and gas, coal, hydropower, biomass energy, energy-saving technologies, smart grid, and energy grid integration has tremendously improved. Leapfrog development has been achieved in a few of these areas, and, in some areas, China is already on par with advanced nations of the world. Independent innovation and technological breakthroughs have been achieved in new-generation nuclear power technologies, power generation equipment manufacturing, efficient and clean coal combustion, wind turbine manufacturing, and dispatching operations in large grids with large-scale renewable energy inputs. However, some of China's core technologies and equipment are still lagging behind those of advanced nations. Moreover, clear weaknesses remain in China's capacity to independently develop original high-end technologies, and there is a pressing need to strengthen research and development efforts.

2.1 Generation III nuclear power technologies are now being widely utilized while extensive research have begun on Generation IV nuclear power technologies. However, China's research efforts in nuclear power are still relatively decentralized

The safety of China's nuclear power technologies is in-line with the highest international safety standards and is continuously being improved. Therefore, China's nuclear power plants have excellent safety standards and outstanding operational records, with their level of risk being under control. Independently developed Generation III pressurized water reactors (PWRs) are now entering widespread application. These reactors have been implemented in domestic demonstration projects and are being sold overseas. Extensive research on Generation IV nuclear power technologies has also begun. The construction of a fast-neutron reactor demonstration project will begin soon, and a high-temperature gas-cooled reactor demonstration project is already under construction. However, the nuclear power technologies of China are still far behind those of advanced nations in a few important aspects. Uranium exploration in China has not been extensively conducted and China's capacity for fuel assembly fabrication is still inadequate. In terms of dry storage and post-processing of depleted uranium and nuclear waste disposal, China has not reached internationally advanced levels and must increase efforts to close this gap. Furthermore, nuclear power plants life extension and decommissioning works have only just begun in China and there are notable shortcomings in China's technical reserves. There are certain technologies in the nuclear power sector that could have profound impacts on future energy structures: uranium extraction from seawater, fast-neutron reactors, the thorium-uranium fuel cycle, fusion power, and hybrid nuclear fission-fusion [2,3]. Each of these technologies has a distinct and unique technological roadmap, which caused the scattering of nuclear power research efforts in China.

2.2 Industry chains for wind power equipment have been established, but there are significant gaps between China and advanced nations regarding wind farm designs and intelligent operation and maintenance technologies

China's wind turbine manufacturing technologies are essentially on par with other advanced nations, with domestic industry chains for wind power equipment already established. Blades, gears, turbines, and electronic control systems for MW-level wind turbines are now being produced domestically on industrial scales. A significant body of experience has been accumulated in the design, construction, operation, and monitoring of onshore wind power facilities. Furthermore, well-refined centralized wind power dispatching systems and technical support systems have been established. The optimization of wind farm designs, operations, and maintenance based on big data and Internet technologies are important for increasing the conversion efficiency, power generation capacity, and cost efficiency of wind power generation. In advanced nations, mature solutions are already available in these areas. Consequently, there is a large gap between China and other advanced nations in big data analysis, big data standards, and big data-based wind farm optimization in the wind power sector [4,5]. In the future, designs and operations/maintenance technologies for different types of wind farms will be developed using big data in order to provide technical support for the optimization and operation of large-scale wind power bases and distributed wind energy systems.

2.3 Photovoltaic power generation and concentrated solar power technologies have reached maturity, whereas solar photochemical technologies remain in laboratory research phases

Photovoltaic (PV) technologies have developed at a rapid pace in China. Comprehensive industry chains have been established for the production of polycrystalline silicon, silicon ingots and wafers, and solar cells and components, as well as the application of PV systems and the manufacture of specialized equipment. The monocrystalline and polycrystalline solar cells that are commercially produced in China have achieved efficiencies greater than 20% and 18%, respectively. Hence, China has gained an edge over the rest of the world in the production of highly efficient low-cost silicon solar cells. However, there is a sizeable gap between China and other advanced nations in the field of silicon-based thin film solar cells in terms of the production of advanced materials, key equipment, and technical level [6,7]. China should strengthen efforts to achieve breakthroughs in the development of light, flexible, and wearable solar cells and conduct pilot demonstrations. Additional efforts should be committed to the study of artificial photosynthetic solar fuels to achieve original breakthroughs related to key basic scientific questions as soon as possible. A deep understanding of the microscopic mechanisms of photochemical conversion processes and the thermodynamic and kinetic principles of the catalytic reactions in photosynthesis must be attained in order to enable the development of materials, theories, methods, and strategies for artificial photosynthesis.

2.4 Electrochemical energy storage is currently the most common and mature form of energy storage; research about hydrogen energy storage must be sustained

China has made great strides in physical and chemical energy storage technologies and holds a reservoir of intellectual properties in these areas, making it one of the frontrunners of the world in energy storage technologies. At present, almost all lithium-ion battery parts are being produced domestically, and China has transitioned from the catch-up stage to being in-step with advanced nations. China currently ranks first in the world regarding the production of lithium-ion batteries. Several important breakthroughs have been achieved in relation to materials, components, system integration, practical application, and key technologies of flow batteries. Significant progress has also been made regarding the operational mechanisms of lead-carbon batteries and the development, design, and manufacturing of high-performance carbon materials [8]. Sodium-sulfur batteries and lithium-sulfur batteries have already begun to enter practical usage. Tremendous progress has been made in relation to electrode materials, electrolytes, and modularization of supercapacitors. As for other emerging energy storage technologies, further improvements need to be made in terms of power density, environmental suitability, safety, cycle life, and production cost [9]. Research on renewable energy-based water electrolysis should be intensified to enable the large-scale application of hydrogen energy storage.

2.5 Although conventional exploration technologies have reached maturity, there are weaknesses in China's unconventional oil and gas exploration technologies and smart sensor technologies

Prior to 2035, the development of China's energy sector will focus on the stabilization of oil production and the acceleration of natural gas production due to the current state of China's energy needs, energy structures, and energy sector. Therefore, China will face numerous challenges related to the development of exploration technologies and other key technologies. China has made significant progress in geophysical exploration technologies, as Chinese companies now own a 46% of the global market share in the land seismic exploration technology market and have gained pricing power. However, the equipment manufacturing capabilities of China are still behind those of other advanced nations. China has developed mature conventional technologies for land seismic exploration and advanced land seismic technologies for the exploration of complex mountainous terrain. However, the development of exploration technologies for unconventional oil and gas resources, like off-shore reservoirs and natural gas hydrate reservoirs, is still in preliminary stages. The development of deep-sea technologies, deep-water drilling equipment, and auxiliary equipment is currently in the early stages of commercialization and rapid development. Chinese companies already possess the ability to develop design schemes for deep-water drilling and well completion in depths exceeding 1 650 m and to optimize design and equipment/technology selections for deep-and-cold water drilling [10,11]. Although significant breakthroughs have been attained in numerous areas, many inadequacies still persist. For instance, China still lacks the experimental capabilities to develop microelectromechanical systems (MEMS)-based omnidirectional high-resolution multi-wavelength multi-component land seismic technologies [12]. Against the backdrop of smartization-dominated technology trends, the development of well drilling and well completion technologies has been constrained by the shortcomings of China in high-end micro/nano sensors and smart materials. The bottlenecking of these technologies has caused the proportion of hard-to-recover reserves in China's total petroleum reserves to grow continuously.

2.6 As coal combustion is the primary mode of coal usage in China, innovations in clean coal combustion technologies will always be important for the energy developments of China

Clean coal combustion involves ultra-supercritical coal combustion technologies; industrial coal-fired boilers; scattered coal for civilian usage; water-saving technologies for coal-fired power plants; carbon capture and storage (CCS); carbon capture, utilization, and storage (CCUS); and coal combustion waste management. China currently leads the world in terms of ultra-supercritical coal combustion technologies, water-saving technologies for coal-fired power plants, coal combustion waste management, and CCS. However, certain technologies and key equipment in these outstanding areas still require further development or improvement. The overall technological level of industrial coal-fired boilers in China is still relatively poor, as the operational efficiency of these boilers is 20% lower than international advanced levels. Furthermore, effective technological measures for the control of decentralized coal emissions from civilian usage have yet to be developed. In terms of construction of CO_2 pipelines and research in cutting-edge technologies such as chemical looping combustion, China still lags behind advanced nations (e.g., the United States).

2.7 Hydropower technologies in China are among the most advanced in the world and are important for ensuring the realization of green, sustainable, and low-carbon development

China ranks first in the world in terms of total hydropower reserves, installed hydropower capacity, and annual hydropower output. Breakthroughs have been achieved in key technologies and scientific problems regarding large-scale hydropower plants, including the development of 7×10^5 kW-grade hydropower generators, the design of 300 m-tall dams, ultra-large underground power stations, transient analysis in complex water conveyance systems, and the design of gigantic water conveyance structures. Nonetheless, there are many important technical problems related to hydropower development that have yet to be addressed. For example, the stability of gigantic water turbines and their systems is still problematic, and additional research is needed for the development of high-head hydropower stations and run-of-river diversion hydropower plants. The study of key technologies and scientific problems related to the stability of superhigh-head superhigh-capacity impulse turbines and high-capacity high-head tubular turbines is also urgently needed. In relation to the field of pumped-storage hydroelectricity, it is still necessary to conduct further research on variable-speed pumped-storage hydroelectricity, key technologies of seawater pumped-storage power stations, and control technologies for the coordination of pumped-storage hydroelectricity with other energy sources. Regarding the field of small hydropower, China is still far behind other advanced nations in the manufacturing of small low-head high-flow hydropower equipment, technologies for the stable long-term operation of micro-hydroelectricity plants, and automated turbine control technologies [13].

2.8 Biomass energy has tremendous potential for development and it is necessary to bolster the development of biomass energy technologies and the construction of industrial systems for biomass energy

The development and usage of biomass energy in China is plagued by a series of problems, including low utilization rates, small production scales, high production costs, ineffective industrial systems and production chains, weak R&D capabilities, and lack of technological innovation. China is already ranked second in the world in terms of total installed biomass capacity, but the biomass-based power generation technologies of China are still far inferior to European nations in terms of boiler systems and auxiliary equipment/processes. Furthermore, bottlenecks are still present in core technologies like feedstock preprocessing, efficient energy conversion, and equipment development [14]. Biodiesel technologies have reached industrial application, but little research has been carried out on the mechanisms of biomass conversion into liquid fuel, efficient long-lived catalysts, and enzymatic conversion. The bonding and forming mechanisms of biomass molded fuel are still unclear. Moreover, the collection and nurture of energy plant species have just begun in China. Since each research group focuses on different aspects of energy plant collection, research efforts in this area have been relatively decentralized and mainly focused on a few well-known energy plant species. The breeding of energy plants based on molecular genetics is still in preliminary stages, while the usage and propagation of high-quality varieties is still very limited.

2.9 China is actively promoting the progressive stepwise integration of smart and energy grids through smartization, transparentization, and intellectualization

China is leading the world in smart grid technologies like ultra-high-voltage (UHV) transmission, voltage source converter-based high voltage direct current transmission (VSC-HVDC), large-capacity power storage, large power grid dispatching, active distribution networks, microgrids, and energy conversion equipment. However, power grids and energy networks have always operated independently of each other, and there are severe industry barriers to the formation of cross-system networks and a lack of trading mechanisms for the energy market. These shortcomings prevent multi-energy complementation and severely limit improvements in energy and operational efficiency that could have been obtained via interconnection, interconversion, and independent trading of different energy sources. At present, the power and energy systems of China are being continuously reformed. This has driven the integration of the smart grid with energy networks and the construction of several demonstration projects related to the Energy Internet, multi-energy complementary systems, and incremental power distribution networks. In view of China's growing demands for primary energy and the development of smart materials and communication technologies, the integration of the smart grid with energy networks is expected to steadily progress, reaching the milestone levels of smartization, transparentization, and intellectualization in due time. Three different modes of the smart grid and energy network integration will arise: (1) the widespread smart grid interconnection to enable concentrated consumption of renewable energy and cross-regional energy resource allocation [15,16], (2) the use of region-level and user-level integrated energy systems to enable local consumption of renewable energy and enhance end-use energy efficiency, and (3) the use of smart equipment and the Ubiquitous Network to establish zero-marginal-cost energy networks and enable the emergence of new energy production and consumption models.

3 Energy technology system

Fig. 1 illustrates a renewable energy-based technology system for the complementary integration of multiple energy sources and energy networks, which uses electricity as the primary type of end-use energy. This figure may be divided into nine areas (coal, oil and gas, nuclear power, hydropower, wind power, solar power, biomass energy, energy storage, as well as smart grid and energy network integration) in the vertical axis and three levels (innovative, forward-looking, and disruptive technologies) in the horizontal axis.

The coal sector should focus on high-efficiency low-emission coal combustion technologies, coal combustion waste management technologies, end-use decentralized coal utilization technologies, carbon dioxide capture, transport and utilization, and combined-cycle magnetohydrodynamic (MHD) power generation technologies.

The oil and gas sector should focus on full-waveform inversion seismic exploration technologies, accurate and intelligent directional drilling technologies, intelligent well completion and oil production technologies, and bionic drilling systems.

The nuclear power sector should focus on deep uranium exploration; optimization, and scale popularization of pressurized water reactors; development of fast reactors and Generation IV reactors; simultaneous development of technologies for the "front end" and "back end" of the nuclear fuel cycle; modular multi-application small reactors; and controlled nuclear fusion.

The hydropower sector should focus on high-head large-flow hydroelectricity technologies; techniques for the construction of hydropower dams; environmentally friendly hydropower technologies; high-dam maintenance techniques; and the integration of smart hydropower plant design, smart manufacturing, smart power generation, and smart watershed management.

The wind power sector should focus on the assessment and monitoring of wind energy resources, design of high-power wind turbines, wind turbine maintenance and fault diagnosis, and high-altitude wind power generation technologies using high-power wireless power transmission.

The solar sector should focus on the upgrading of crystalline silicon solar cells, concentrated solar power (CSP), thin-film solar cells, solar-hydrogen production technologies, and light and flexible wearable solar cells.

The biomass sector should focus on the co-processing of urban and rural waste and poly-generation; preparation of functional biomass materials; and the selection, breeding, and planting of energy plants.

The energy storage sector should focus on high energy density and safe lithium battery technologies, high-cycle lead-carbon batteries, liquid sodium-sulfur batteries, lithium-sulfur batteries, and solid oxide electrolysis cell (SOEC) water-electrolysis hy-

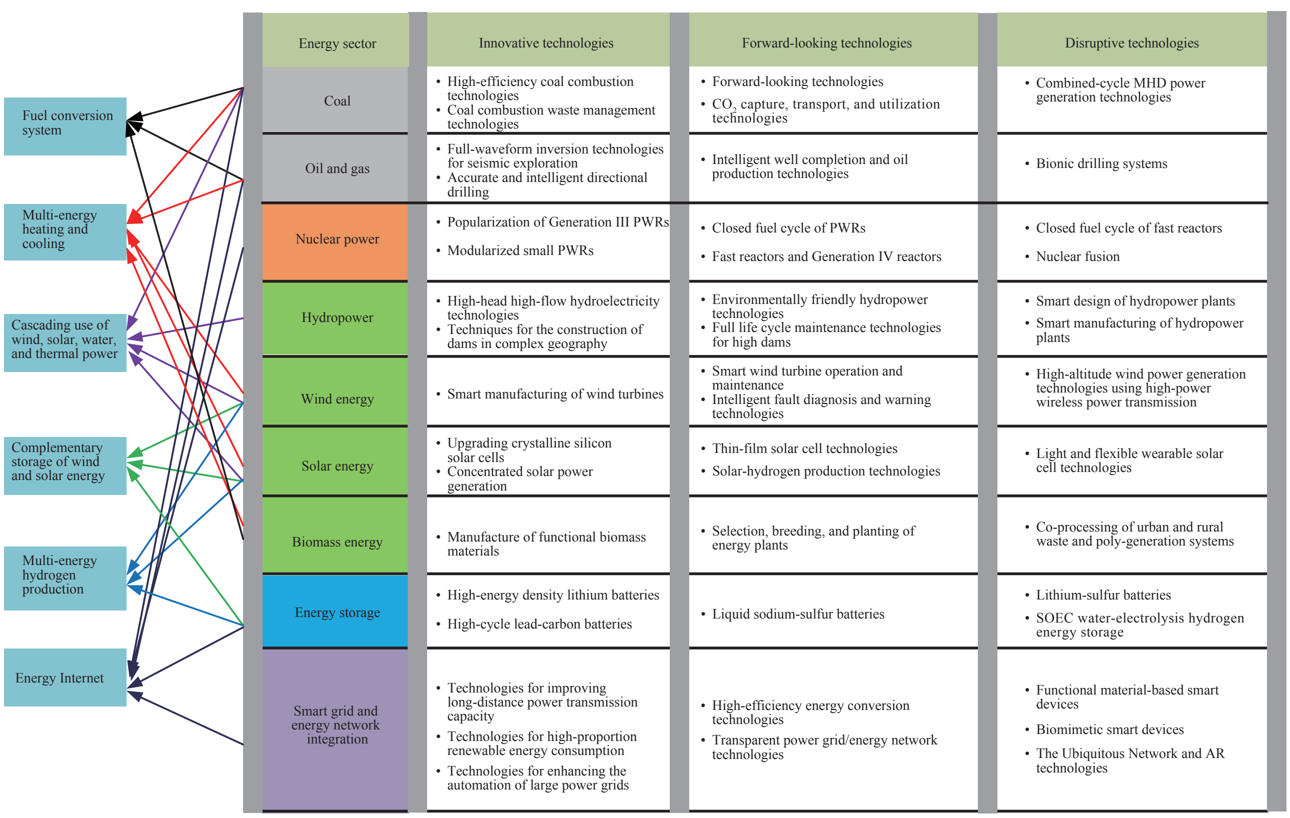

Fig. 1. An energy technology system for China.

drogen energy storage.

Smart grid and energy network integration should focus on the improvement of long-distance power transmission technologies, technologies for increasing the proportion of renewable energy consumption, technologies for increasing the automation of large power grids, high-efficiency energy conversion technologies, transparent power grids/energy networks, functional material-based smart devices, biomimetic smart devices, the Ubiquitous Network, and virtual reality.

By integrating the technologies of each energy sector, fuel conversion systems can be used to perform coal-to-gas, coal-to-oil, biomass-to-diesel, and biomass-to-gas conversions, thus supplementing oil and gas resources. Coal, natural gas, wind, and solar energy can be combined to form multi-energy heating, cooling, and hydrogen production systems. Electricity can be converted into other types of energy when ample amounts of wind power and PV solar power are available. The conversion of coal into hydrogen also enables the decarbonization of the energy system and the production of clean energy. In addition, cascading energy use can be achieved by combining energy storage technologies with wind energy, hydropower, PV energy, and thermal power generation.

4 Development roadmap for the energy technology revolution

In Fig. 2, it is shown that the energy technology revolution of China will be implemented at the technical and systemic levels in three stages, which will be marked by three milestone years: 2020, 2030, and 2050.

By 2020, China's capacity for independent innovations in the field of energy will be greatly improved, and breakthroughs will be achieved in several innovative technologies. In particular, breakthroughs will be attained in high-efficiency clean coal combustion technologies and the first steps towards the formation of a coal-based energy-chemical industry system will be taken. Breakthroughs will also be achieved in deep exploration and exploitation technologies for unconventional oil and gas resources through the establishment of basic research systems for micro/nano well logging and smart materials [17]. Hydropower resources and long-distance UHV grids will be utilized in conjunction with breakthroughs in CSP, PV, and wind power generation technologies to form a renewables-based technology system and energy production system. The Generation III nuclear reactors that were independently developed in China will be packaged as generalizable products, which will drive the development of nuclear power production chains. The construction of small modularized PWR demonstration projects will begin. The proportion of nuclear power, renewable energies, and new energy sources will steadily increase, thus reducing CO_2 emissions. The direction of future energy developments and energy structure transformations will fundamentally shift the development of energy consumption away from extensive growth. The energy self-sufficiency rate of China will be maintained above 80% through the formation of a comprehensive energy security system. China's reliance on other countries for technical equipment, key components, and materials for the energy sector will diminish substantially, and the competitiveness of China's energy industries in the international arena will improve significantly. China will thus enter the ranks of nations with capability for energy technology innovation and establish an energy technology innovation system with Chinese characteristics [18].

By 2030, a comprehensive energy technology innovation system that suits China's domestic conditions will be established. This will enhance China's capabilities for independent energy technology innovations in all aspects and allow China to gain parity with other advanced nations regarding energy technologies [19]. Biomass liquid fuel technologies will achieve large-scale commercial applications. Furthermore, breakthroughs will be attained in information assurance technologies and advanced

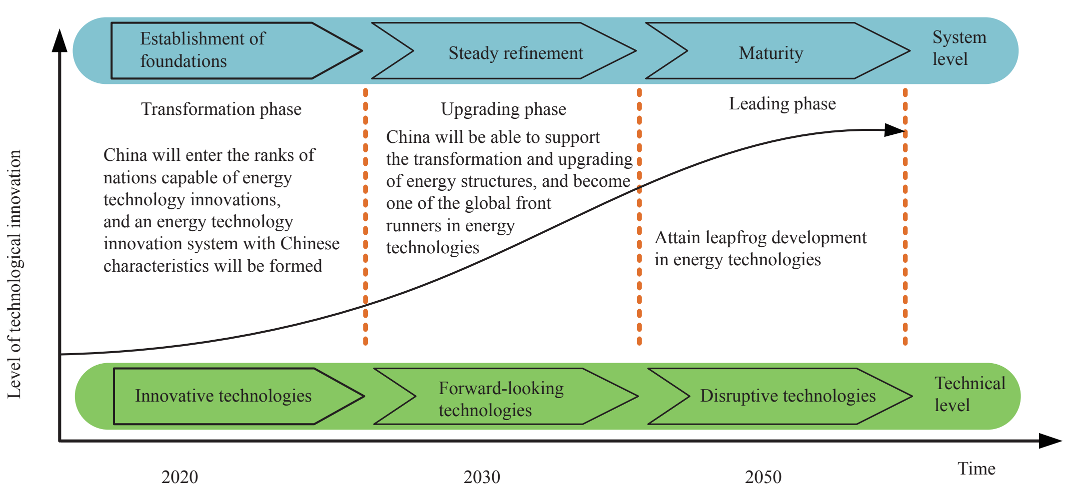

Fig. 2. Development roadmap for the energy revolution of China.

power generation materials, equipment, and technologies, which will allow the realization of low-loss high-capacity power transmission and efficient energy end-use. Preliminary steps will be taken to establish new distributed microgrids power systems based on PV and wind power generation in order to start the integration of the smart grid with energy networks. Breakthroughs like accident tolerant fuels will be attained in nuclear power safety technologies, which will fully eliminate large-scale releases of radioactivity and improve the competitiveness of nuclear power. Closed fuel cycle of PWRs will be brought to realization and the development of nuclear power industry chains will be carried out in a coordinated manner. Generation IV reactors, like sodium-cooled fast reactors, will mature and breakthroughs will be attained in key technologies (e.g., nuclear fuel breeding and transmutation of high-level radioactive waste). Active efforts will be made to investigate the multipurpose application of small modularized reactors (including small PWRs, high-temperature gas-cooled reactors, and lead-cooled fast reactors). The large-scale application of nuclear power, renewable energies, and new energies will be realized. The energy self-sufficiency rate of China will be maintained at high levels and international energy resources will be utilized more carefully. The development of forward-looking technologies will drive fundamental changes in the energy structures of China, support the harmonious and sustainable development of China's energy industries and ecological environment, and initiate the construction of a modern energy system. These efforts will make China one of the leading nations of the world in energy technologies [20].

By 2050, disruptive technologies will transform the concepts and development roadmaps of traditional energy technologies and revolutionize the energy sector. Breakthroughs will be achieved in gas hydrate development and utilization technologies, oil replacement technologies, hydrogen energy-use technologies, and fuel cell vehicle technology. In addition, closed fuel cycle of fast reactors will be completed, PWRs and fast reactors will be developed in conjunction with each other, and the construction of a nuclear fusion demonstration project shall be strived for. Energy-saving technology systems will be established and a low-carbon multi-energy structure with an equal mix of fossil fuel energies, new energies, renewable energies, and nuclear power will be constructed [21]. With a mature and comprehensive energy technology innovation system, China will become a globally important scientific research center for energy technologies, hold the high ground in energy technology innovations, and lead a new round of scientific and industrial revolution in energy production and consumption. The efficiency levels and energy technologies and equipment of China will reach internationally advanced levels and China will become a major participant in global energy governance. A modern energy system will be established to ensure the modernization of China's energy structures.

5 Important initiatives for the energy technology revolution

5.1 The "resource protection amidst resource development and resource development amidst resource protection" concept must be maintained in hydropower developments, while efforts should be committed to the development of environmentally friendly small-to-medium sized hydropower plants

Hydroelectricity should be developed with vigor, alongside the appropriate management of environmental protection and hydroelectricity development. Hydroelectricity developments should prioritize the protection of the environment based on the principles of active, scientific, and rational development and usage. Resource development should be conducted amidst resource protection and vice versa, managing the relationship between resource protection and development in an appropriate and rational manner. The scientific outlook on development should be thoroughly implemented to promote harmony between mankind and nature. As the sustainable utilization of water resources is necessary for sustainable socioeconomic development, the conservation of river health is a fundamental prerequisite for the development and usage of water resources. Forward-looking research should be conducted about the construction of small-to-medium low-head high-flow hydropower plants, techniques for stable long-term operation of micro-hydropower plants, automated turbine control technologies, design criteria for environmentally-friendly small hydropower plants, fish-friendly hydro turbine design, "Internet + small hydroelectricity/smart cloud power station" technologies, and ecological criteria for the construction of environmentally-friendly high dams. These efforts will promote the popularization and industrialization of new technologies, and ultimately support the establishment of clean and renewable energies.

5.2 Biomass should be developed according to local conditions and requirements, but biomass development should not be limited to biomass-based power generation

An integrated mode of development that is not strictly limited to biomass-based power production should be selected according to biomass types and economic/environmental conditions of each locality. We suggest that domestic garbage should be converted into biomass-based liquid fuels like biodiesel and cellulosic ethanol, while human/animal waste and agricultural/forestry waste should be converted into producer gas. Medium-to-large sized biogas plants should be constructed to purify and store biogas. Agricultural/forestry waste can also be transformed into biomass briquettes to form biomass molded fuels and prepare biochar via biomass pyrolysis. A comprehensive recycling system for straw, domestic garbage, and agricultural/forestry waste should be constructed to strengthen the coordination between biomass purchasing, transportation, storage, and processing.

5.3 Solar power technologies should be vigorously developed and the strategic position of solar power in the transformation of China's energy structures should be clarified

Solar energy is readily available, clean, and safe. China has large extensions of land that are suitable for solar power generation and buildings also have very large light-receiving areas. We suggest that solar power generation should be adopted as the primary technical direction of renewable energy utilization and the core of long-term energy technology development roadmaps. Solar power should be vigorously developed and popularized to reduce the cost of solar cells, drive the development of solar cell efficiency-improving technologies and processes, and holistically improve industry chains for crystalline silicon solar cells. The development of thin-film solar cells should be accelerated in conjunction with the bolstering of research efforts to develop technologies for the industrialization of silicon-based thin-film solar cells. The aim of these efforts should be to fully exploit the unique advantages of thin-film solar cells in terms of their flexibility, lightness, and versatility, and capture a dominant position in the space-, area-, and weight-sensitive power generation market.

5.4 New energy sources should be developed in a distributed manner and consumed locally to avoid high-capacity long-distance power transmission

Energy investment structures should be optimized. New energy investments should be delayed in regions that exhibit severe wind and solar curtailment and energy-intensive loads should be used to locally consume the excess power produced by new energy sources. Distributed PV power generation, distributed wind power generation, smart grid, and smart storage technologies should be promoted and applied vigorously to rapidly transform the mode of new energy developments in China from a "large-scale development and long-distance transmission" mode to a "distributed development and local consumption" mode. The use of long-distance power transmission to transmit new energy sources to load centers should be avoided.

5.5 Multi-energy complementation technologies should be broadly applied to support the transformation of China's energy structures

On the energy supply side, the ability of different energy sources to substitute and complement each other should be fully exploited to develop and optimize multi-energy systems in a complementary and coordinated manner, with the objective of forming a stable, efficient, and clean energy supply system. On the energy consumption side, electricity substitution; combined cooling, heat, and power; smart microgrids; and industrial park-level integrated energy systems should be used (according to local conditions) to satisfy end-user demands for electricity, heating, cooling, and natural gas. This will enable the coordinated supply of multiple energy sources and the comprehensive cascading of energy use. A complementary multi-energy demonstration project has been deployed in Xiong'an New Area to construct a world-class, green, and efficient smart energy system.

5.6 The development of advanced materials and devices should be strengthened to support the development of disruptive technologies

The development of advanced materials, basic devices, integrated chips, and microsensors required for China's energy technology revolution should be bolstered. In addition, the development of flexible thin-film solar cells in China should be accelerated to enable their application in wearable technologies and achieve the industrialization of non-toxic wearable solar cell technologies. The development of water electrolysis-based hydrogen production using energy derived from solar, wind, and hydropower curtailment should be accelerated. Micro/nano-exploration technologies (microelectromechanical/ nanoelectromechanical systems, nanosensors, and nano-optical fibers) should be used to construct a technological system for intelligent oil and gas exploration. Microsensor-based transparent power grids should be studied and piloted to support the development of disruptive energy technologies.

5.7 A national clean energies research center should be established to allow China to seize global leadership of energy technologies

A national clean energies research center should be established to resolve the major scientific problems confronting the strategic needs of China's energy sector. This will: (1) strengthen multi-energy system integration, interdisciplinary multi-energy studies, government–industry–academia integration, human–finance–material resource integration, and system/mechanism innovations; (2) initiate technological innovations in fundamental, forward-looking, and strategic technologies related to clean energy; (3) bolster the collaborative innovation of energy alongside basic sciences such as materials science, information technology, chemistry, control technologies, and mechanical engineering; (4) drive the integrated innovation of energy technologies alongside applied technologies such as big data, cloud computing, the Internet of Things, artificial intelligence, robotics, and smart manufacturing; (5) resolve the major technology and equipment bottlenecks that are obstructing the energy technology revolution of China.

5.8 Construct a national-level big data center for the energy sector to support the decision-making processes of national energy policies

A national-level big data center for the energy sector should be constructed to support the multi-dimensional acquisition, transmission, storage, analysis, and application of multi-energy data throughout the entirety of China, thus enabling the rapid extraction and application of in-depth knowledge from these data. This will facilitate a holistic understanding of energy utilization in each province and industry, allow large national platforms to allocate resources in a rational manner, and provide a scientific basis for the formulation of policies to drive the energy structure transformation of China. The unification of information acquisition, aggregation, and storage standards for the energy sector will resolve the problem of informational island isolation in multi-energy systems, which is caused by multi-sourced heterogeneous data. Furthermore, to ensure energy information security, information assurance in the energy sector should be enhanced, and information assurance technology protection and management should be implemented.

References

[1] Zhang Y H, Lu B P. Prediction of global energy trend and analysis on energy technology innovation characteristics [J]. Natural Gas Industry, 2015, 35(10): 1–10. Chinese.

[2] Kang X W, Fu W. IEA/NEA new technology roadmap for nuclear energy (part one): Situation and trend of nuclear energy development in the world [J]. China Nuclear Industry, 2016 (4): 35–37. Chinese.

[3] Kang X W, Fu W. IEA/NEA new technology roadmap for nuclear energy (part two): Expected action for the development of nuclear energy in the world [J]. China Nuclear Industry, 2016 (5): 34–37. Chinese.

[4] Qian B Z. Wind energy technology and its application [M]. Beijing: China Science Publishing & Media Ltd., 2010. Chinese.

[5] Shen D C. The development course of wind energy technology in China [J]. Solar Energy, 2017 (8): 9–10. Chinese.

[6] Tang Y H, Xie J. Current development of photovoltaic technology [J]. Renewable Energy Resources, 2005 (3): 68–69. Chinese.

[7] Chow T T. A review on photovoltaic/thermal hybrid solar technology [J]. Applied Energy, 2010, 87(2): 365–379.

[8] Divya K C, Østergaard J. Battery energy storage technology for power systems—An overview [J]. Electric Power Systems Research, 2009, 79(4): 511–520.

[9] Li J L, Ma H M, Hui D. Present development condition and trends of energy storage technology in the integration of distributed renewable energy [J]. Transactions of China Electrotechnical Society, 2016, 31(14): 1–10. Chinese.

[10] Sun W B, Cao Y, Lu Y. Development of marine electromagnetic oil and gas exploration technology and its application [C]. Tianjin: 2017 Geophysical Technology Symposium of the Chinese Petroleum Society, 2017. Chinese.

[11] Yu Y. Development and innovation of oil and gas exploration technology [J]. Technology and Market, 2016, 23(11): 136. Chinese.

[12] Liu H. Optimization design of MEMS vector sensor in oil and gas pipeline inspection system [D]. Taiyuan: North University of China (Master's thesis), 2014. Chinese.

[13] Paish O. Small hydro power: Technology and current status [J]. Renewable and Sustainable Energy Reviews, 2002, 6(6):537–556.

[14] Yuan Z H, Wu C Z, Ma L L. Principle and technology of utilization of biomass energy [M]. Beijing: Chemical Industry Press, 2005. Chinese.

[15] Chen S Y, Song S F, Li L X, et al. A review of smart grid technology [J]. Power System Technology, 2009, 33(8): 1–7. Chinese.

[16] Li L C, Zhang Y J, Chen Z X, et al. Merger between smart grid and energy-net: Mode and development prospects [J]. Automation of Electric Power Systems, 2016, 40(11): 1–9. Chinese.

[17] National Development and Reform Commission of the PRC. Innovation action plan of energy technology revolution (2016—2030) [R]. Beijing: National Development and Reform Commission of the PRC, 2016. Chinese.

[18] Chinese Academy of Sciences. China's road map of energy science and technology development to 2050 [M]. Beijing: China Science Publishing & Media Ltd., 2009. Chinese.

[19] Energy Research Institute of the National Development and Reform Commission of the PRC. Reshaping energy: A roadmap for energy production and consumption revolution in 2050 [R]. Beijing: Energy Research Institute of the National Development and Reform Commission of the PRC, 2016. Chinese.

[20] China National Renewable Energy Center. China's renewable energy development route 2050 [R]. Beijing: China National Renewable Energy Center, 2015. Chinese.

[21] Energy Research Institute of the National Development and Reform Commission of the PRC. Research on the development scenarios and ways of 2050 high proportion renewable energy in China [R]. Beijing: Energy Research Institute of the National Development and Reform Commission of the PRC, 2015. Chinese.