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Energy Revolution under Vision of Carbon Neutrality

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Abstract: Climate change has emerged as one of the major challenges faced by mankind. It has become a non-traditional global security issue, which causes a serious threat to the survival and sustainable development of human being. China's commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 has important strategic significance for building a modern socialist country with harmonious coexistence between human and nature. Facing the challenge of China's carbon peak and carbon neutrality, this study proposes, through energy revolution, to promote electric decarbonization and zero carbon emission from electricity and fuels on the energy supply side, and to enhance energy utilization efficiency, re-electrification, and intelligence on the energy demand side. Thus, a clean, zero-carbon, safe and efficient energy system will be established with new energy as the main body and fossil energy plus carbon capture, utilization, and storage (CCUS) and nuclear energy as the guarantee. **DOI:** 10.16418/j.issn.1000-3045.20210812001-en

Keywords: carbon neutrality; energy revolution; zero carbon emission from electricity; zero carbon emission from fuels

Climate change has emerged as one of the major challenges faced by mankind. Since the first Industrial Revolution, discovery and utilization of fossil energy including coal, petroleum, and natural gas have greatly improved productivity and driven big boom of the society while resulting in severe problems such as pollution and climate change. Over the last 200 years, carbon dioxide (CO_2) emissions from burning fossil energy have accumulated to 2.2 trillion tons, while the global CO_2 concentration in the atmosphere keeps rising. Especially in the last 50 years, CO_2 concentration experienced rapid growth (Figure 1), with CO_2 volume fraction in the atmosphere reaching 419×10^{-6}① in April 2021, and the global mean ground surface temperature has risen by 1.1 °C. In 2018, the United Nations Intergovernmental Panel on Climate Change released a special report, *Global Warming of 1.5°C* [1], noting the observed reality of global warming that will impact mankind much more badly than predicted earlier. A 2 °C increment in temperature will incur unbearable impact on the world, so we have to keep the temperature rise within 1.5 °C. Global warming caused by emitted greenhouse gases of which CO_2 accounts for the largest share has become a non-traditional global security issue and imposed a serious threat to the survival and sustainable development of human being.

To contribute to the global ecological civilization and build a community of shared future for mankind, Chinese President Xi Jinping announced at the 75th UN General Assembly in September 2020 that China aims to peak carbon emissions by 2030 and achieve carbon neutrality by 2060②. This commitment not only manifests the responsibility of China as a great country but also drives the upgrading of the energy structure, industry structure, and economic structure in China. It is of great strategic significance for China's high-quality development and building a modernized socialist country with harmonious coexistence between human and nature.

1 Challenge in achieving carbon peak and carbon neutrality

The Chinese economy has boomed over the 40 years of reform and opening-up. In 2019, China's gross domestic product (GDP) was over 14 trillion US dollars, ranking the second in the world, whereas the GDP per capita just topped 10 000 US dollars, ranking the 67th in the world (Figure 2). As the world's largest developing country, China still suffers from unbalanced and inadequate development and faces a variety of arduous tasks in economic development and livelihood improvement. The demand for energy and the carbon emissions by China are still rising. The first challenge is how to accomplish carbon peak and carbon neutrality by transforming energy structure, industry structure, and economic structure while ensuring economic and social development.

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① https://keelingcurve.ucsd.edu/.

② http://www.xinhuanet.com/politics/leaders/2020-09/22/c_1126527652.htm.

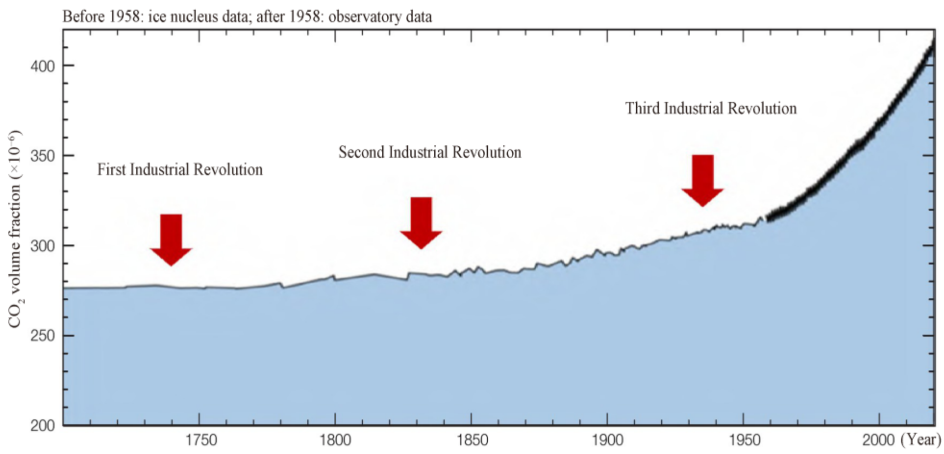

Figure 1 Trends in atmospheric CO_2 since the first Industrial Revolution

Data source: Scripps Institution of Oceanography at UC San Diego (https://keelingcurve.ucsd.edu/).

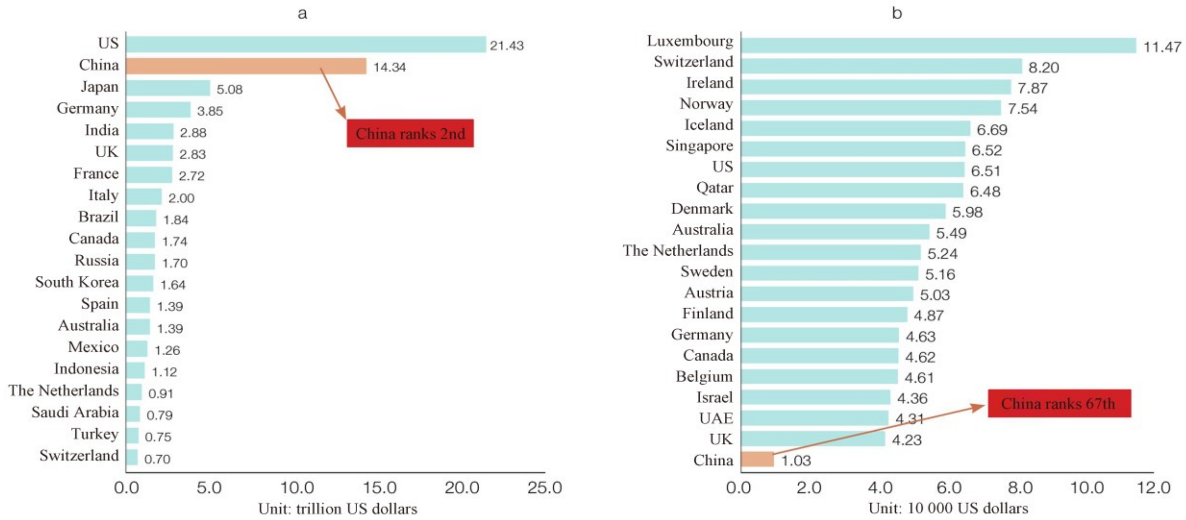

Figure 2 Global GDP (a) and GDP per capita (b) rankings in 2019: Top 20 countries in the world

Data source: The World Bank (https://data.worldbank.org/indicator/NY.GDP.PCAP.CD).

The total energy consumption of China ranked the first in the world in 2020, accounting for more than 1/4 of the world's total while the CO_2 emissions accounted for 1/3 of the world's total [2]. As for the structure of energy consumption in China (Figure 3), fossil energy was still dominant, with a proportion over 84% in 2020 [2]. More than half of energy consumption in China was from coal, far higher than what coal accounts for in the global structure of energy consumption. In terms of power generation, 68% of total electricity generated in China was thermoelectricity in 2020 [3]. The two biggest carbon emitters in China were power generation and heating (51%) and manufacturing, (28%) (Figure 4) ③. Major countries of the EU had fulfilled carbon peak by the 1990s, and the US achieved the goal in 2007. Major countries of the EU proposed fulfillment of carbon neutrality by 2050, making a time span of over 60 years from carbon peak to carbon neutrality. However, owing to the late start in China, the time window from carbon peak (2030) to carbon neutrality (2060) was less than half that of those European countries. This implies a shorter time for China to transform fossil energy system, which accounts for 84%, into an energy system with net zero carbon emission. Such a heavy load at such a tight schedule is the second challenge.

In terms of climate change and control of greenhouse gases across the society, China still lags behind developed countries in people's voluntariness, corporate consensus,

③ https://www.iea.org/data-and-statistics/data-browser?country=CHINAREG&fuel=CO2%20emissions&indicator=CO2BySector.

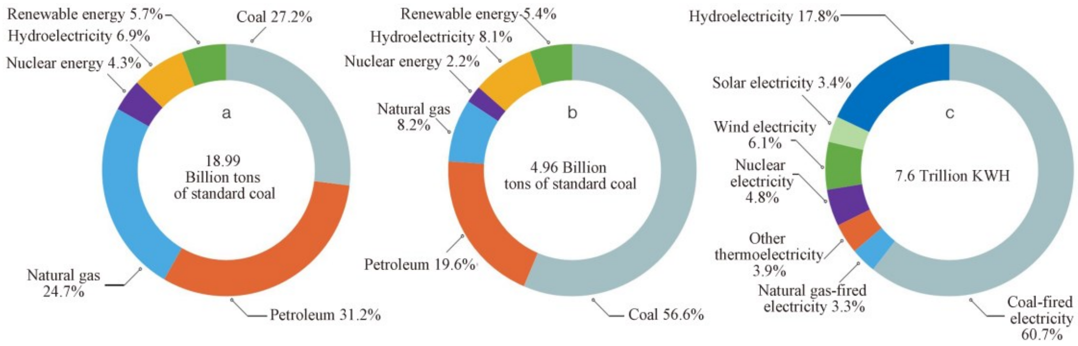

Figure 3 Global energy consumption (a) and China's energy consumption (b) and power generation (c) by type in 2020

Data source: BP [2], China Electricity Council [2].

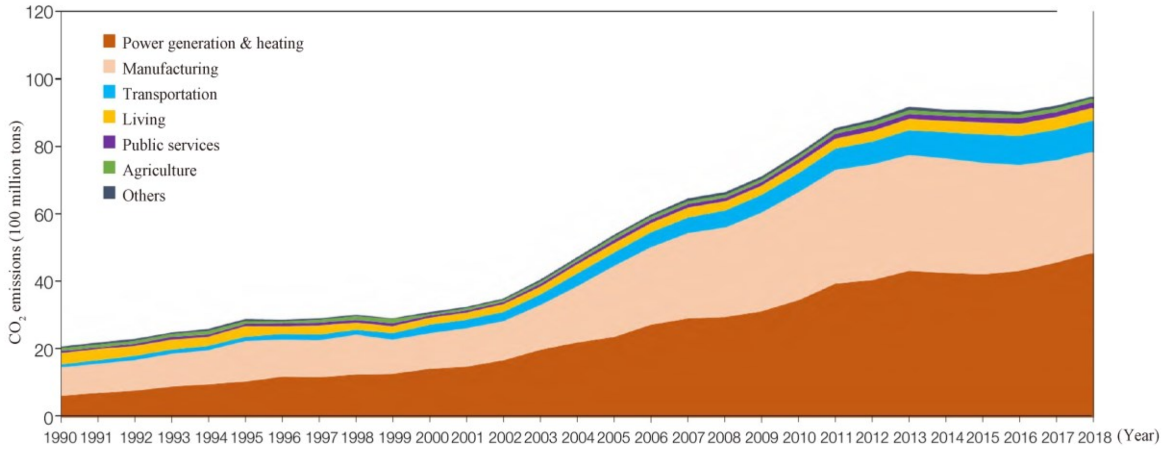

Figure 4 China's carbon emissions by sector from 1990 to 2018

Data source: IEA (https://www.iea.org/data-and-statistics/data-browser?country=CHINAREG&fuel=CO2%20emissions&indicator=CO2BySector).

technology availability, market mechanisms, and laws and regulations. For example, since the Kyoto Protocol took effect, regional carbon trading systems have been established in major countries/regions for fulfillment of the commitment to carbon emission reduction. During 2005–2015, 17 carbon trading systems were established, covering 4 continents. However, the national carbon emissions trading system was not up in China until July 2021. The third challenge is the proceeding of China's carbon trading system.

In response to the aforementioned challenges, it is imperative for China to expedite systematic transformation of the economy and society oriented to carbon peak and carbon neutrality, and launch energy revolution so as to make new breakthroughs in the supply, consumption, technologies and systems of energy.

2 Energy revolution under the vision of carbon neutrality

Carbon neutrality is a green revolution aiming at constructing a brand-new industry system with zero carbon emissions. In cannot be achieved without revolutionary and transformational breakthroughs in technology. In the future, the energy revolution presents 5 trends: zero carbon emission from electricity and fuels at the supply side and efficient, re-electrified and intelligent utilization of energy at the demand side (Figure 5). Ultimately a clean, zero-carbon, safe and efficient energy system will be established in China, which is primarily made up of new energy and safeguarded with fossil energy plus carbon dioxide capture, utilization and storage (CCUS) and nuclear energy.

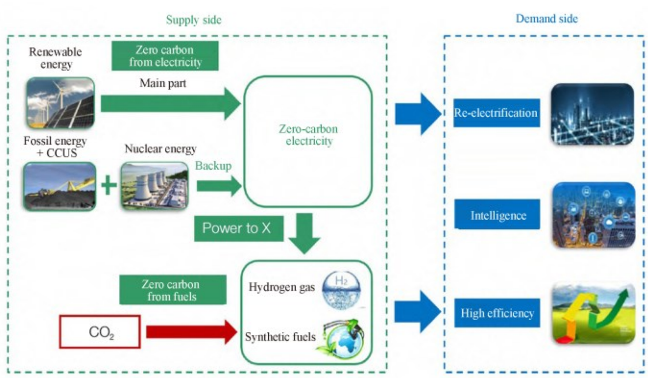

Figure 5 Energy revolution towards carbon neutrality

2.1 Future energy revolution at the supply side

2.1.1 Zero carbon emission from power generation

Currently as high as 41% of carbon emissions around the globe are from the power generation sector, and 51% of carbon emissions in China are from electricity and heating [5]. Therefore, decarbonization and zero carbon in the electricity industry is key to reaching the goal of carbon neutrality.

(1) For the sake of decarbonization and zero carbon in the electricity industry, the first thing is to boost power generation from renewable energy. In the recent 10 years, renewable energy advanced by leaps and bounds in China and its volume that was developed and utilized secured the first place in the world. In 2020, the total electricity from renewable energy amounted to 2.2 trillion KWH ④, accounting for 29.5% of the national electricity consumption in China. By the end of 2020, the installed renewable energy capacity reached 930 million kilowatts, which accounted for 42.4% of the total (Figure 6). The cost of power generation from renewable energy kept decreasing, and the global cost of photovoltaic electricity dropped by about 85% in 2010–2020 [4]. In June 2021, the State Power Investment Corporation Limited quoted as low as 0.147 6 CNY/KWH in phase 1 of the 200 thousand kilowatt project in Zhengdou, Ganzi Prefecture, Sichuan Province, setting a record low for photovoltaic power plant projects in China ⑤. It is predicted that the installed wind power and photovoltaic power capacity will reach as much as 1.6–1.8 billion kilowatts by 2030 and top 5 billion kilowatts in 2050 [5].

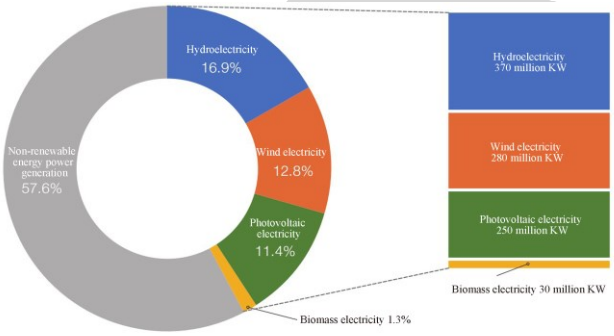

Figure 6 China's installed power generation by type, as of end of 2020

Data Source: National Energy Administration (http://www.nea.gov.cn/2021-03/30/c_139846095.htm).

(2) For the sake of decarbonization and zero carbon in the electricity industry, the pivot is construction of new electricity systems mainly made up of new energy. Double uncertainties and fluctuation from high percentage of new energy and huge load impose a big challenge on power balance and safe running of the power grid. Thus it is imperative to transform the traditional power supply mode, i.e., load following power generation, for more flexible electricity systems. The hard nut to crack is intensive interaction between generation, grid, load and storage as well as their regulation in regional electricity systems for enhanced flexibility of electricity systems based on power electronics, prediction and management of power supply and demand based on big data, and establishment of discretely autonomous transactions based on mutual trust. It is necessary to intensify the reform on the electricity regime and innovate the market mechanism and business model. Drawing on the off-grid photovoltaic electricity and wind electricity all over China, every building can be turned into a miniature power plant. Such technologies as virtual power plants, smart microgrids, and energy storage are to be boosted. More new energy capacity needs to be deployed to generate and absorb more new energy electricity as well as to turn regular coal-fired electricity from current baseload electricity to peak regulated electricity for decarbonization and net zero carbon. It is a substantial transformation to construct novel electricity systems dominated by new energy, in which German experience is worth referencing. Germany announced ditching nuclear energy and coal in 2022 and 2038, respectively, and construction of an energy usage system consisting of 100% renewable energy in 2050 ⑥. Legislation is prioritized during promotion of renewable energy in Germany, and off-grid photovoltaic electricity, wind electricity, biomass electricity generation and energy storage sets are set up nationwide. Absorption of renewable energy is effectively facilitated and balance between supply and demand over the power grid is improved through big data-based prediction and management of both the supply end and the demand end of electricity on the web-enabled platform for electricity trading and servicing. In Germany, thanks to high proportion of renewable energy, regular thermoelectricity has shifted from baseload electricity to peak regulated electricity, thus accomplishing transition of the energy structure.

(3) For the sake of decarbonization and zero carbon in the electricity industry, net zero carbon emission can be achieved via CCUS for power generation from fossil energy. At present, CCUS is the key technology for large-scale utilization of fossil energy with zero carbon emission. Thermoelectricity incorporating CCUS will offset the fluctuation of power generation from renewable energy, thereby providing backup electricity and ensuring the flexibility of power grid. "New energy power generation + energy storage" and "thermoelectricity + CCUS" will be indispensable combinations, the intensive collaboration of which will be key to a clean, safe and efficient energy system with zero carbon emission in the

④ http://www.nea.gov.cn/2021-03/30/c_139846095.htm.
⑤ https://guangfu.bjx.com.cn/news/20210622/1159464.shtml.
⑥ https://www.bundesregierung.de/breg-en/issues/climate-action/lower-co2-emissions-1795844.

future. The International Energy Agency (IEA) predicts that under the circumstance of sustainable development, all the coal generator sets without carbon capture and storage (CCS) will be discontinued worldwide before 2045, with 1 000 TWH of electricity produced by coal integrated with CCS technologies [6]. Therefore, it is suggested to increase investment in research and development of CCUS technologies, lower cost and energy consumption, develop novel absorbents, adsorbents, and membrane-separating materials, and crack the enabling technologies for all the steps including carbon capture, separation, transportation, utilization, sequestration, and monitoring. It is important to establish the systems for CCUS standards and management, CCUS-enabled carbon emission trading system, tax incentive policies, and the ecology of carbon finance as soon as possible in an effort to push forward technology paradigms for million-ton CO_2 capture and utilization in thermoelectricity generator sets, leading to CCUS commercialization.

2.1.2 Zero carbon emission from fuels

Zero carbon emission from fuels involves production of renewable fuels, including hydrogen, ammonia, and synthetic fuels, from renewable energy like solar power and wind power. Production of renewable fuels for zero-carbon electricity will create a brand new offline “generation-storage-load” form for utilization of renewable energy (Figure 7), which can make transportation fuels and industrial fuels potentially independent of fossil energy, thereby achieving net zero carbon emission from fuels. As a revolutionary technology with huge potential, renewable energy is able to provide brand new solutions for transition of national energy strategies and fulfillment of carbon neutrality.

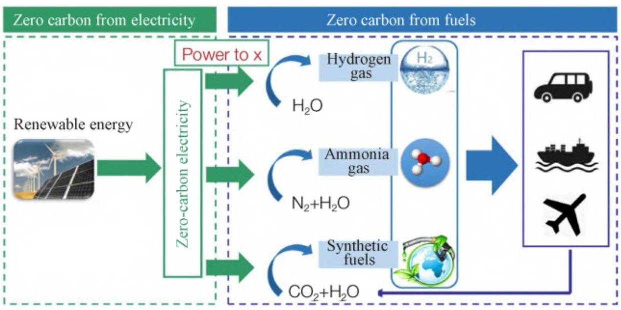

Figure 7 Renewable fuel production based on zero-carbon electricity

Synthetic renewable fuels are produced by CO_2 reduction of renewable energy via electrocatalysis, photocatalysis, and thermocatalysis. The end products are hydrocarbon fuels or alcohol-ether fuels that feature high energy density, convenient transportation and filling, low cost of application, and reuse of existing infrastructure like gas stations. In 2006, the Nobel laureate in chemistry George Andrew Olah et al. [7] proposed in their work *Beyond Oil and Gas: The Methanol Economy* that renewable energy can be used to convert CO_2 from industrial emissions and in the nature into carbon-neutral alcohol-ether fuels. In 2018, 4 academicians of the Chinese Academy of Sciences, Shi Chunfeng, Zhang Tao, Li Jinghai, and Bai Chunli [8], jointly published a study on *Joule*, pointing out the key for mankind to acquiring, storing, and supplying solar energy is how to convert it into stable, storable, and energy-rich chemical fuels so that Liquid Sunshine can shape the future world. In recent years, the technologies that use renewable energy to convert CO_2 to synthetic fuels have drawn great attention of major developed countries and regions. Carbon Recycling International built in Iceland the world’s first commercial methanol plant based on recycled CO_2 where geothermal power generation is followed by electrolysis of water to produce hydrogen gas (H_2) which will be used to synthesize methanol with CO_2. The company achieved a capacity of 4 000 tons ⑦ for methanol in 2014. In October 2020, the thousand-ton Liquid Sunshine demonstration project for fuel synthesis led by Li Can, Academician at Dalian Institute of Chemical Physics, Chinese Academy of Sciences and his team was up and running successfully in Lanzhou ⑧. The EU launched the Energy-X project to explore the recycled use of carbon-derived energy with CO_2 as medium. The US Department of Energy founded Liquid Sunlight Alliance (LiSA) with focus on photo/electro-reduction of CO_2 into liquid fuels. The Renewable Synthetic Fuels Research Center was founded at Shanghai Jiao Tong University, aiming to research and develop renewable synthetic fuel systems based on zero-carbon electricity. Hepburn et al. [9] at Oxford University published a paper on *Nature*, predicting 4.2 billion tons of CO_2 will be transformed to synthetic fuels around the globe by 2050.

In order to obtain renewable synthetic fuels via sunlight, water, and CO_2 in a real sense, it is imperative to research the fundamental theories and enabling technologies for renewable synthetic fuels. Renewable synthetic fuels are to be designed considering the products of CO_2 reduction and the interaction between fuels and motor units. The structure-property relationship of catalysts is to be built at the molecular level for design and functional customization of efficient CO_2-reducing catalyst systems. On top of that, CO_2-reduced synthetic fuel systems with high energy efficiency will be constructed to accomplish highly selective conversion from CO_2 to liquid fuel molecules and synthesis of renewable fuels.

2.2 Future energy revolution at the demand side

Highly efficient, re-electrified, and intelligent utilization of energy needs to be expedited at the demand side.

⑦ Can the coversion of CO_2 to methanol solve the carbon emission problem of coal chemical industry. ASIACHEM, 2016 (in Chinese).
⑧ https://www.cas.cn/cg/cgzhld/202101/t20210112_4774334.shtml.

2.2.1 High efficiency

Efficient utilization of energy and energy saving with carbon emission reduction are rudimentary work for carbon peak and carbon neutrality. Since 2012 China's energy consumption per unit of GDP has cumulatively decreased by 24.4%, well above the global average decreasing rate. However, it is worth noticing that China's energy consumption per unit of GDP in 2019 was still 50% higher than the global average and about 3 times of that in the UK and Japan [2]. There is still considerable potential for energy saving and carbon emission reduction. China need to strengthen the research, development, and promotion of the cutting-edge technologies for energy saving, water saving, materials saving, and decarbonization, and facilitate energy saving and decarbonization across the key sectors including electricity, manufacturing, transportation, and construction. The sectors and enterprises with high energy consumption and high carbon emissions such as electricity, steel, petroleum refinery, non-ferrous metals, and construction materials, together with public transit vehicles and public buildings, need to be adapted with energy-saving and decarbonization technologies at a faster pace to reduce energy consumption per unit of GDP and carbon emission intensity.

2.2.2 Re-electrification

Re-electrification refers to high-level electrification based on zero-carbon electricity on top of traditional electrification. The energy in the future carbon neutral society will be pivoted on zero-carbon electricity. In 2018, the global level of electrification, namely the portion of electric energy in final energy consumption, was merely 19% while that of China was 25.5% [10]. It is projected that the global level of electrification will rise beyond 50% in 2050 [11]. On the basis of expedited supply of zero-carbon electricity, accelerated re-electrification in such areas as manufacturing, construction, and transportation is an important approach to higher energy efficiency as well as decarbonization and zero carbon in energy utilization.

2.2.3 Intelligent transformation

Intelligent transformation involves interconnection between men, energy equipment and systems, and energy services via information technology and controlling technologies such as Internet, Internet of Things (IoT), artificial intelligence, big data, and cloud computing. It will lead to profound synergy among power source, power grids, load, and energy storage as well as intensive integration of energy flow and information flow. The networking of a variety of distributed sources of power and massive load with each element endowed with intelligence enables efficient production, trading, and utilization of energy as well as shared energy infrastructure, which is an important means to improve energy efficiency and maximize local absorption of renewable energy. The blockchain technology provides data or information with such features as footprints all the way through, traceability, transparency, and collective maintenance, which will change the production and trading modes of the energy systems and enable point-to-point production and trading of new energy as well as shared infrastructure. For example, in the future, using mobile apps, people can readily sell extra photovoltaic electricity on their own roof to the strangers nearby who need to recharge their electric vehicles. This point-to-point transaction system will make individual nodes in the energy system independent producers/consumers.

2.3 Megatrends in the evolution of energy

The megatrends in the evolution of energy toward carbon neutrality are to boost decarbonization in electricity and zero carbon emission from electricity and fuels at the supply side, and highly efficient, re-electrified and intelligent utilization of energy at the demand side through energy revolution. Fossil energy, particularly coal, will be turned into backup energy. Net zero carbon emission can be realized by CCUS alongside steady development of nuclear electricity. On the basis of that, a clean, zero-carbon, safe and efficient energy system will be established in China, which is primarily made up of new energy and safeguarded with fossil energy plus CCUS and nuclear energy.

In terms of the form of energy production, the existing tree-like structure (generation-transmission-distribution-use) of the electrical system will be shifted to a flat structure where a large number of autonomous elements of distributed energy are interconnected reciprocally. This interconnection enables layer-wise connection and absorption for renewable energy, thus constructing novel electricity systems dominated by new energy.

In terms of the stakeholders of energy production and consumption, the energy producer and consumer independent of each other will become an organic whole. As the distributed energy system and technologies like smart microgrids and local area network are increasingly mature, together with wide availability of electric vehicles, discrete power sources and active load in the power grid will keep increasing. As every building is a miniature power plant, the users who used to be at the demand side will play dual roles of both consumers and producers, becoming independent energy producers/consumers.

In terms of energy structure, fossil energy will gradually shift from mainstay energy to backup energy, with its percentage in primary energy consumption slashed. By contrast, renewable energy will shift from complementary energy to mainstay energy with its share continuously hiked. Energy utilization will go from high carbon to low carbon, ultimately entering the era of zero-carbon energy. This change will be revolutionary.

3 Conclusions

(1) Energy revolution under the vision of carbon neutrality

includes zero carbon emission from electricity and fuels at the supply side, and efficient, re-electrified and intelligent utilization of energy at the demand side. Decarbonization in electricity and zero carbon emission from electricity are the key and top priority in achieving the goal of carbon neutrality. The energy in the carbon neutral society will be pivoted on zero-carbon electricity. Maximal efforts should be taken to speed up the development of non-carbon-derived electricity, increase its supply and construct novel electricity systems dominated by new energy.

(2) In response to carbon neutrality, fossil energy, particularly coal, will turn into backup energy. Currently CCUS is the key technology for large-scale utilization of fossil energy with zero carbon emission. Thermoelectricity incorporating CCUS will offset the fluctuation of power generation from renewable energy, thereby providing backup electricity and ensuring the flexibility of power grid. “New energy power generation + energy storage” and “thermoelectricity + CCUS” will be indispensable combinations which will make a clean, zero-carbon, safe and efficient energy system primarily made up of new energy and safeguarded with fossil energy plus CCUS and nuclear energy.

(3) Carbon peak is an increment change and carbon neutrality a substantial change. The substantial change of carbon neutrality cannot be reached only through the incremental change during carbon peaking. Carbon neutrality cannot be achieved without energy revolution, green revolution or systematic revolution in the economy and society. Future energy oriented to carbon neutrality will be centered at a brand new energy system strategically supported by a variety of revolutionary technologies.

(4) Fulfillment of the goal of carbon peak and neutrality will not counter economic and societal development. It is “changing track” rather than “passing on the same track”. It redefines the way of resource utilization in the human society, being not only a challenge but also an opportunity. Carbon neutrality will take lead in constructing a brand new industry system with zero carbon emission. Development and utilization of energy based on natural endowment will transition to development and utilization of new energy based on technological innovation. Whoever leads innovation in zero-carbon technologies will be the leading racer on the new racing track with the potential to lead next round of industrial revolution.

(5) Energy revolution oriented to carbon neutrality is far more than an energy issue or environmental issue but also a global, systematic issue. It cannot be done at one shot but progressively and circuitously. The pathways for energy revolution are subject to scientific design and decision-making based on technology, market, policy, regulations, etc.

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