

Study on Paths and Countermeasures to Promote Green and Low Carbon Transition of Energy Sources

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Abstract: The "14th Five-Year Plan" explicitly proposes to build a clean, low-carbon, safe and efficient energy system, and promote the transformation of energy consumption to electrification and low-carbon. Based on the current situation of China's energy development, this paper analyses the structural adjustment pressure, technological shortcomings, power system construction challenges, energy security risks, heavy economic structure and insufficient market driving force faced in the green and low-carbon energy transition, and proposes countermeasures, such as diversified energy supply, breakthroughs in key technologies, the construction of a new type of power system, the deepening of international cooperation, the economic structural adjustment and the optimization of the market mechanism. The study shows that through policy guidance, technological innovation and international collaboration, China can effectively achieve a green and low-carbon energy transition, help achieve the goals of carbon peaking and carbon neutrality, and promote high-quality economic development.

Keywords: Energy transition; Green and low carbon; Carbon neutrality; New power systems; Policy recommendations.

1. Introduction

The 14th Five-Year Plan clearly states that China should focus on building a clean, low-carbon, safe and efficient energy system, substantially increasing the proportion of non-fossil energy consumption, accelerating the construction of wind power and photovoltaic power generation bases, and promoting the transformation of energy consumption to electrification and low-carbonisation, while at the same time strengthening the regulatory capacity of the energy system to ensure energy security and green development, in order to achieve the goals of peak carbon and carbon neutrality. Promoting the green and low-carbon transformation of energy can help reduce greenhouse gas emissions and respond to global climate change, as well as promote the optimisation and upgrading of the energy structure and improve the efficiency of energy use. The development of green energy industry can create new economic growth points and employment opportunities, promote technological innovation and industrial upgrading, and enhance the sustainable development of the economy. By reducing reliance on fossil energy, it can lower energy costs and import dependence and improve energy security, thereby providing a more solid foundation for stable economic growth.

Against the backdrop of volatile changes in the global landscape, the frequency of geopolitical conflicts has led to a significant increase in the risk of disruptions to the energy supply chain and industrial chain. The frequent occurrence of extreme weather events globally, such as extreme heat and cold waves, can also have a serious impact on energy production and supply, putting energy supply in a constant state of emergency. The energy sector is in a critical period of low-carbon transition, with instability in the supply of new energy sources challenging the security of the power system, and a lack of investment in fossil energy sources further exacerbating market volatility. In this transition process, it is particularly important to build a new power system that is safe

and efficient, clean and low-carbon, flexible and nimble, and intelligently integrated, which not only improves the security of energy resources, but also promotes the energy supply revolution and ensures energy security. At the same time, the construction of a new type of power system is also a key initiative to address climate change and realise the green and low-carbon transformation of energy.

2. Current Status of Energy Development in China

China's energy industry is stepping into a new stage of high-quality development, presenting the dual characteristics of optimising supply and demand patterns and upgrading structures. In recent years, the growth rate of energy demand has dropped significantly, the mismatch between traditional energy supply and demand has been effectively mitigated, and breakthroughs have been made in green transformation. It is worth noting that China has built the world's largest low-carbon power infrastructure network, new energy industry chain in the international market to establish a significant competitive advantage, electric vehicles, photovoltaic modules and energy storage equipment exports continue to lead the world [1]. Statistics show that the country's total energy supply has increased by more than 20 per cent compared with five years ago, building a solid foundation for economic and social development and livelihood protection.

In terms of the transformation and upgrading of the power system, the process of cleaner and lower-carbonisation has accelerated significantly. As of the latest statistical cycle, the installed capacity of non-fossil energy power generation facilities exceeded 157 gigawatts (GW), climbing to 53.9 per cent of the total installed capacity, for the first time surpassing the installed capacity of traditional thermal power. This structural shift is in line with the urgent needs of global climate governance, and marks the deep transformation from traditional fossil energy to renewable energy, which is not only a strategic choice to guarantee national energy security,

but also a key path to cultivate new momentum for green economy.

According to the Annual Energy Development Report 2023, the total installed capacity of power generation facilities in the country reached 2,920 GW with an annual growth rate of 13.9 per cent. Of this, installed photovoltaic (PV) power generation surpassed 610 GW, a surge of 55.2 per cent year-on-year, while installed wind power reached 440 GW, an annual growth rate of 20.7 per cent. Despite the accelerating process of clean energy substitution, fossil energy still dominates. Total energy consumption that year reached 5.72 billion tonnes of standard coal, an increase of 5.7%. The specific composition shows that: coal accounted for 55.3 per cent of consumption, a year-on-year decrease of 0.7 percentage points; natural gas and renewable energy accounted for 26.4 per cent, an increase of 0.4 percentage points. The data indicate that the traditional energy system based on coal and oil will remain the mainstay in the medium term.

3. Problems in the Energy Transition Process

3.1. Great Pressure to Adjust the Energy Structure

Coal accounts for more than half of China's energy consumption structure, and it will be difficult to fundamentally transform this coal-dominated energy structure in the short term. The large-scale replacement of coal requires the rapid development of new and renewable energy sources, which has no precedent in human history, and requires time for technical, economic and social adaptation. At the same time, China is the world's largest energy-consuming country, and the adjustment of the energy structure will not only affect the domestic economy, but also have a far-reaching impact on the global energy market.

3.2. Technological Shortcomings and Lack of Innovation Capacity

Against the backdrop of an accelerating global carbon neutral process, the innovation of the energy system is facing the dual challenges of a generational gap in technology and an imperfect innovation ecosystem. This transformation process needs to break the "green-economy-security" triad paradox, and build a complex system model that includes industrial value chain reconstruction (e.g., digital transformation of traditional energy-intensive industries), energy supply chain resilience enhancement (establishment of a 120-day buffer mechanism for the reserve of strategic resources), social cost control (to maintain the volatility of energy prices at less than one-third of the GDP growth rate), and labour force structural adaptation (planning for the training of 500,000 traditional energy workers each year. worker transfer training) and other multi-dimensional complex system models [2]. The technical audit shows that there is a significant generation gap between China's 26 key technology nodes such as the mass production process of fourth-generation photovoltaic chalcogenide modules (conversion efficiency is 1.2 percentage points lower than the international benchmark), the integration of Gigawatt-grade all-vanadium liquid current energy storage systems (energy density of only 1/3 of that of the Li-ion system), and the digital twin-driven smart grid architecture, and there is an urgent need for the implementation of major special projects

through the "new type of state-run system" to focus on breakthroughs. Broadband semiconductor power electronics, supercritical CO₂ cycle power generation, green hydrogen metallurgical coupling and other subversive technology clusters.

In the field of carbon-negative technology, according to the latest assessment of the Global Carbon Capture and Storage Institute (GCCSI), China's CCUS Technology Maturity Index (TMI) is 58.7, lagging behind North America by 6.3 index points. The specific technology gap is reflected in: ① high energy consumption per unit of carbon capture (energy consumption of coal-fired power plant capture reaches 3.2GJ/tCO₂, which is 18% higher than the international best practice); ② imperfect assessment system of the storage site (only 8% of the three-dimensional geological modeling of the suitable stratum has been completed); ③ insufficient efficiency of the chemical use of the conversion (the selectivity of methanol made of CO₂ is 12% lower than the international advanced level). It is suggested to build a three-level innovation system of "basic research - engineering verification - commercial promotion", focusing on the development of metal-organic skeleton (MOF) oriented adsorption materials, submarine storage leakage monitoring fibre-optic arrays, biomass-coupled CCUS negative emission systems and other frontier directions, and striving to build a million-tonne full-flow demonstration project by 2025, so as to achieve the reduction of capture and integration costs to the economic threshold of US\$40/tCO₂.

3.3. Difficult Task of Building a New Power System

With the large-scale development of new energy sources, the operation of the power system is facing more uncertainties, and it is urgent to enhance the system's flexible adjustment capacity and improve the safe operation of the energy system and its ability to withstand risks. In the process of large-scale application of renewable energy, the stability of the energy network is facing a significant test. The inherent intermittent characteristics of new energy make it more difficult to balance power supply and demand, which requires the system to have a more efficient flexible regulation mechanism, while strengthening the security redundancy and anti-disturbance performance of the infrastructure. The new power system needs to realise the optimised planning of power quantity guarantee, power flow layout, new energy layout and system regulation capacity. This involves not only technical issues, but also market mechanisms, policy support and other challenges [3]. In order to achieve the sustainable development of the green energy system, it is necessary to optimise the design of power supply reliability, transmission and distribution network architecture, spatial distribution of clean energy and dynamic response capacity. This process not only involves technological breakthroughs, but also requires simultaneous promotion of market mechanism innovation, policy support measures to improve the systemic reform of the institutional level.

3.4. Diversification of Energy Security Risks

In the process of green and low-carbon energy transition, energy security risks are showing a diversified trend. With the adjustment of the energy structure, new energy security issues continue to emerge, such as the stability of electricity supply and the volatility of energy prices. At the same time, the uncertainty of the international energy market also poses a

challenge to China's energy security, and risks need to be reduced by diversifying energy supply and strengthening international cooperation.

3.5. Biased Economic Structure and Difficult Industrial Transformation

China's economic structure is heavily weighted, with high energy-consuming industries such as iron and steel, cement and chemicals occupying an important position, making economic structural adjustment and industrial transformation a difficult and heavy task. Energy transformation requires not only technological progress, but also in-depth adjustment of the industrial structure, which involves huge economic and social costs and requires the synergy of policy guidance and market mechanisms.

3.6. Market Drivers Need to Be Strengthened Urgently

For a long time, China has had low prices for high-carbon energy and high prices for low-carbon energy, with large differences in energy prices among regions, and the task of using market means to promote energy transition is quite arduous. It is necessary to enhance the driving force of the market for low-carbon energy and promote the optimisation of the energy consumption structure through the price mechanism, tax policy and other means.

4. Countermeasures to Promote Green and Low-Carbon Energy Transition

4.1. Diversified Energy Supply and Policy Incentives

Coal accounts for more than half of China's energy consumption structure, and it will be difficult to fundamentally transform this coal-dominated energy structure in the short term. In the face of this challenge, China needs to adopt a diversified energy supply strategy to reduce its reliance on coal by increasing the use of clean energy, such as natural gas and nuclear energy. At the same time, the government should formulate and implement policies such as carbon tax and carbon trading to incentivise enterprises to reduce the use of coal and increase investment in clean energy. In addition, strengthening cooperation with other countries to introduce advanced technologies, share best practices and reduce transition costs is crucial to easing the pressure of energy restructuring.

4.2. Breakthroughs in Key Technologies and Introduction of Professionals

Energy transformation needs to break through the triple constraints of greenness, economy and security, and take into account various factors such as economic development, industrial transformation, security of supply and stable employment. China still has shortcomings in new energy technology, energy storage technology, smart grid technology, etc., and needs to increase investment in R&D and enhance independent innovation capability. Especially in carbon capture, utilisation and storage (CCUS) and other carbon-negative technologies, there is still a gap between China and the international advanced level, and we need to strengthen scientific and technological research. The government and enterprises should increase R&D investment in new energy, energy storage and smart grid technologies, as well as

strengthen STEM education, cultivate professionals in the energy field, and introduce advanced technologies through international co-operation, while strengthening local innovation.

4.3. New Power System Construction and Policy Support

Through the construction of a "synergistic development system of multiple resource elements", the company has coordinated the system integration of the power supply side, grid side, load side, energy storage side and the hydrogen energy industry chain, and innovatively constructed a resilient grid architecture that combines wide-area interconnection and regional autonomy. At the level of grid optimisation, efforts will be made to implement the "main distribution co-development strategy", focusing on strengthening the iterative upgrading of smart distribution grids, deploying advanced equipment such as flexible distribution devices and smart energy measurement terminals, and synchronising the low-carbon transformation of power generation and the transformation of the in-depth electrification of the energy end-use terminals. Based on this, the "New Electric Power System Development Roadmap (2025-2035)" should be compiled and implemented, a government-enterprise-research collaborative innovation mechanism should be established, and the participation of multiple market players should be stimulated through franchising, mixed ownership reform and other modes.

In the dimension of basic theory innovation, it is recommended to set up a new type of power system national key laboratory cluster, focusing on breakthroughs in virtual synchronous machine technology, wide-area coordinated control technology, power electronic converter cluster control and other "neck" technologies. In terms of standardisation, it is necessary to accelerate the development of 12 core standards such as "Active Distribution Grid Planning and Design Guidelines" and "Multi-energy Complementary System Operation Regulations", and simultaneously promote the docking with the International Electrotechnical Commission (IEC) standard system. According to the planning goal, by 2035, "three vertical and four horizontal" ultra-high voltage backbone network will be formed, through the inter-regional DC transmission project to achieve the efficient connection between the western renewable energy base and the eastern load centre, and relying on the digital twin technology to build an intelligent scheduling system with milliseconds response capability, so that the power grid has the sponge characteristics of "dynamic sensing - autonomous decision-making - elasticity and recovery".

In view of the development trend of distributed energy penetration rate exceeding 65%, there is an urgent need to reconstruct the technical paradigm of power distribution grid: ① construct flexible interconnection device based on power electronic transformer; ② research and development of intelligent grid-connection interface supporting plug-and-play; ③ set up microgrid group coordinated scheduling mechanism; and ④ develop self-healing control system with the ability of dynamic reconfiguration. In the field of international cooperation, it should deeply participate in the smart grid implementation agreement of the International Energy Agency (IEA), jointly carry out cross-border power internet demonstration projects, and focus on breaking through the bottleneck of multinational grid frequency

cooperative control technology.

Energy storage system construction, it is recommended that the implementation of "100GW level energy storage development plan", focusing on the layout of lithium-ion batteries, liquid current batteries, compressed air energy storage and other technology routes, the establishment of the "power generation side - grid-side - user-side" three-stage energy storage configuration standards. Policy protection level, can design "green power quota + financial subsidies + carbon quota trading" combination of incentive programmes, the implementation of the virtual power plant operator VAT that is refundable preferential, and through the renewable energy development fund for key equipment research and development to give special subsidies.

4.4. Energy Security Risks and International Cooperation

In the process of green and low-carbon energy transition, energy security risks are showing a diversified trend. With the adjustment of the energy structure, new energy security issues continue to emerge, such as the stability of electricity supply and the volatility of energy prices. At the same time, the uncertainty of the international energy market also poses a challenge to China's energy security, and it is necessary to reduce risks by diversifying energy supply and strengthening international cooperation. China should diversify its sources of energy imports, reduce its dependence on a single source of energy, build up strategic energy reserves to cope with market fluctuations and supply disruptions, and strengthen cooperation with energy-exporting countries to ensure the stability of energy supply.

4.5. Economic Restructuring and Industrial Transformation

China's economic structure is heavily weighted, with high energy-consuming industries such as iron and steel, cement and chemicals occupying an important position, making economic structural adjustment and industrial transformation a difficult and heavy task. Energy transformation requires not only technological progress, but also in-depth adjustment of the industrial structure, which involves huge economic and social costs and requires the synergy of policy guidance and market mechanisms. Promoting technological upgrading of energy-consuming industries, improving energy efficiency, incentivising enterprises to undergo green transformation through measures such as financial subsidies and tax breaks,

and providing retraining and employment support for workers affected by the transformation are key to achieving economic structural optimization and industrial transformation.

4.6. Market-Driven and Energy Price Adjustments

For a long time, China has had low prices for high-carbon energy and high prices for low-carbon energy, with large differences in energy prices among regions, and the task of using market means to promote energy transition is quite arduous. It is necessary to enhance the market's driving force for low-carbon energy and promote the optimisation of the energy consumption structure through the price mechanism, tax policy and other means. Adjusting energy prices to reflect environmental costs and make low-carbon energy more competitive, developing green finance to provide financial support for clean energy projects, and raising public awareness of green energy and encouraging consumers to choose low-carbon products are effective ways to enhance market drivers.

5. Conclusion

The green and low-carbon transformation of energy is a systematic project to address climate change and ensure energy security. China needs to integrate policy guidance, technological innovation and international collaboration, break through structural and technological bottlenecks, and gradually build a new energy system with non-fossil energy as the mainstay. Future research can further explore the regional differentiation of transition paths and the optimisation of dynamic policies under the goal of carbon neutrality.

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