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Strategic Thinking of Global Carbon Neutrality Process and the Routing of China

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Abstract

With the rapid spread of global energy crisis, it is urgent to realize the goal of zero-carbon energy revolution and carbon neutrality. From global perspective, developed countries and developing countries are at different stages of economic and social development. There are differences in progress in carbon neutrality laws and regulations, green technology development, and the large differences in policies and perceptions have led to imbalance and uncertainty in global carbon neutrality actions. On this basis, various parties all contribute to low-carbon and green development, while China faces many practical difficulties in achieving the carbon neutrality goal, which are reflected in higher difficulties than developed countries, improved energy security and transformation risks, insufficient core technology and innovation, and large funding gaps. Therefore, China can build a modern energy system, strengthen modern technology and independent innovation, improve the carbon emissions trading system, accelerate the optimization and upgrading of the whole industrial chain, and cultivate the public's awareness of low-carbon consumption to help zero-carbon transformation. The role of China in global climate governance is changing, and it will provide Chinese solutions for the sustainable development of other countries and the realization of carbon neutrality goals.

Keywords

carbon neutrality, low-carbon transition, China's path, energy crisis

1. Introduction

At present, the global energy crisis is imminent, and the energy consumption mode dominated by fossil energy will not be sustainable. With carbon peak and carbon neutrality becoming the national long-term strategic goals, there is a trend to accelerate the transformation of energy structure and promote energy revolution (Pietrosemoli & Rodríguez-Monroy, 2019). Zero-carbon energy revolution is an increasingly new driving force for the mutually beneficial cooperation of the Sustainable Development Goals (SDGs). The process of carbon neutrality, namely the process of fossil energy phasing out or the reduction of coal, petroleum and natural gas, so fossil energy should be paid attention to, and the revolutionary breakthrough of zero-carbon energy is the fundamental guarantee of the target of carbon neutrality. In 2021, global carbon emissions from energy combustion and industrial processes reached 36.3 billion tons, with coal accounting for more than 40 percent of the increase (Caron & Fally, 2022). Carbon emissions from coal, natural gas and petroleum are all near record highs, but renewables and nuclear still account for a larger share of global power generation than coal, despite the rebound in fossil consumption. For China, the construction of modern energy system during the 14th Five-Year Plan period focuses on improving the security and stability of energy supply chain and promoting the process of green and low-carbon energy transformation. By 2025, the proportion of non-fossil energy consumption of China will rise to about 20%; By 2035, China will basically complete the construction of a modern energy system and adopt a green model of production and consumption (Liu et al., 2022).

Under the traditional energy power system, primary energy is converted into electric energy and connected to the power grid. Since there is no direct large-scale and low-cost storage technology for electric energy and the power system must meet the real-time coordination of supply and demand, so the phenomenon of wind, light and water curtailment is still very serious, and it is difficult for renewable energy to be fully consumed, which poses a fundamental challenge to the utilization of renewable energy with high uncertainty. The new technology of hydrogen energy preparation, storage and transportation is becoming a hot topic in the reform of green structure (Yue et al., 2021). Besides, as one of the key technologies that countries all over the world attach great importance to in response to global climate change, carbon capture, utilization and storage (CCUS) has bottlenecks in industrialization, and it can only be used for emergency and standby measures of energy system, which is subject to rigid constraints of nature (Jiang et al., 2021). In the context of global carbon neutrality, a fundamental transformation of development paradigms through clean energy for the implementation of SDGs represent a profound innovation-led opportunity for sustainable development of population patterns, economies, societies and civilizations.

This paper starts with global carbon emissions and carbon neutrality process, and systematically describes the development of green technology. Besides, this paper innovatively divides the global participants into developed countries, developing countries, international organizations and enterprises, and summarizes the contributions of different participants in the global carbon neutrality process. In addition, this paper takes China, the largest developing country in the world, as an example, to show the difficulties China faces in achieving the carbon neutrality goal through different dimensions, and for the first time proposes a systematic solution framework committed to sustainable development, providing important suggestions for China in the formulation of long-term policies about carbon neutrality goal.

2. Governance and Trends of Global Carbon Neutrality

2.1 Overview of Global Carbon Neutrality Regulations and Carbon Emissions

According to the Global Development Report, 136 countries around the world have proposed or are preparing to propose carbon neutrality targets, covering 90% of the world's GDP, 85% of its population and 88% of its carbon emissions (Wu et al., 2022). From the perspective of the way of announcing the commitment, it can be divided into three categories, including policy declaration, legal provisions and commitment submitted to the United Nations. Most countries announce the course of action to the society through national policies, while a few countries, led by UK, France and Germany, incorporate the carbon neutrality goal into the legal system in order to strengthen national support for the realization of carbon neutrality. Fiji and Hungary publicize their carbon neutrality plans by submitting commitments to UN. In terms of time, most countries plan to achieve carbon neutrality by 2050, and developed countries in Europe generally set the carbon neutrality time earlier. Bhutan has adopted a constitution to protect national forests, making it clear that at least 60% of its land area is covered by forests, making hydroelectric power the basis of the national economy and achieving carbon neutrality by 2018. Moreover, Suriname entered the era of negative emissions in 2014 (Zou et al., 2021).

According to the characteristics of carbon-neutral laws and regulations, the countries legislating carbon neutrality targets are all developed countries in the world, and the majority of them are European countries. Specifically, the UK revised its Climate Change Act 2008 in 2019, requiring a 100% reduction in greenhouse gas emission by 2050 compared with 1990. Law on Energy and Climate in France grants the High Commission on Climate to supervise the governance of climate policies, and ensures the realization of the carbon neutrality goal through the pre-event, in-process and post-event legislative regulation. Germany's revised Climate Action Act aims to achieve carbon neutrality by 2045, specifying the carbon emissions allowed in sectors of the economy such as energy, transport, buildings, and launching a national emissions trading system to subsidize electricity prices and public travel. Spain's Climate Change and Energy Transition Act aims to become carbon-neutral by 2050, requiring a 23% reduction in greenhouse gas emissions by 2030 compared with 1990 levels, and seek an increase in the share of electricity generated from clean energy from 40% to 74%. Green Growth Act of South Korea explicitly stated that greenhouse gas emissions would be reduced by 40% from the 2018 baseline and national carbon neutrality goal would be achieved by 2050, thus becoming the 14th country to codify the goal of carbon neutrality. Furthermore, Sweden, Denmark, New Zealand, Hungary have also enacted climate laws, which set a wide example for other countries and regions to adopt a carbon-neutral path (Chen et al., 2022; Tan et al., 2022; Zhao et al., 2022).

In terms of global carbon emissions, half of the countries have reached the carbon peak in the early 21st century, and they are mainly mainstream developed countries and countries with relatively stagnant industrial development. Germany, Romania, Czech Republic and Ukraine reached the carbon peak in the 1990s, while the US reached the carbon peak in 2007, which is over 15 years later than EU countries and some Eastern European member states. In addition, Japan, South Korea, Brazil and

Canada have also achieved the carbon peak in the past 10 years. In the first decade of the 21st century, the economic take-off of developing countries represented by China led to a rapid growth of global carbon emissions. Since 2010, the growth of global carbon emissions has gradually slowed down and started to decline, and in 2019, the growth of global carbon emissions almost stopped (Bruckner et al., 2022). The contribution of carbon emission reduction is mainly from developed EU countries represented by France, and in the context of global carbon emission slowdown, the carbon emission paths of developed economies and emerging economies are quite different. For instance, developed economies, which have already entered the post-industrial era, have reached the peak and maintained stability in the 20th century, while emerging economies have lagged behind in entering the industrial civilization and their carbon emissions are still rising. Since 1990, China's economic growth has accelerated, along with the accelerated urbanization process and the development of heavy and chemical industries, and the carbon emission growth rate has been fast. After China's accession to the World Trade Organization in 2001, carbon emissions also rose sharply, with the growth rate once reaching 18%. After 2011, China began to introduce more strict environmental protection policies, and the growth rate of carbon emissions began to slow down. Currently, China's total carbon dioxide emissions remain at about 10 billion tons (Du et al., 2022).

2.2 Green Technology Development of Carbon Neutrality

The key to achieving carbon neutrality is to replace traditional technologies with green technologies, reduce carbon emissions rather than production capacity, and not actively disrupt the normal order of supply and demand in the absence of green technologies. The main technology to achieve global carbon neutrality is also known as Negative Emission Technologies (NETs). There are three main goals to be achieved, namely improving productivity and technical content, reducing carbon emissions or achieving net-zero emissions, cultivating low-cost advantages with global competitiveness (Budzianowski, 2012). Fossil fuels will continue to play a role in the short and medium term, so achieving carbon neutrality requires the deployment of negative emission technologies. Currently, typical examples of negative emission technologies are carbon dioxide to chemicals, fuel made from carbon dioxide, microalgae production, carbon capture by concrete, carbon capture and storage of bioenergy. Specifically, among the main technologies to achieve carbon neutrality in the world, CCUS technology is an important tool with important promotion and application significance (Vishal et al., 2021). It is not only an indispensable means of renewable energy power and energy saving technology, and a means of deep carbon emission reduction in industrial processes, but also an economic way to achieve low-carbon hydrogen production by combining with natural gas or coal in the future. According to International Energy Agency (IEA), in addition to energy restructuring, CCUS technology is needed for storage and absorption, so as to achieve net zero release by 2070 (Babu et al., 2023).

First of all, the academic circle is constantly exploring the direction of chemical production made from carbon dioxide, and the cutting-edge technology of synthesis starch, glucose and succinic acid is emerging. Only about 13% of the world's petroleum is used to produce petrochemicals, with most of the rest being burned, so changing the chemical process entirely to carbon dioxide production would make little contribution to carbon emission reduction (Sarp et al., 2021). Secondly, enhanced petroleum recovery (CCUS-EOR), a common technique in mature wells, injects carbon dioxide into the well under pressure to make it supercritical, and carbon dioxide is used based on the lowest available cost, mostly from natural resources. However, it has gradually become difficult to adapt to the requirements of complex geological conditions, and about 400 million tons of low-permeability petroleum reserves in China are difficult to develop. In addition, agriculture, deforestation, fertilizer production, account for nearly 30% of global carbon emissions, and the spetroleum under all conventional farming, which uses chemical fertilizers, is almost microbial free (Feng et al., 2020). Agriculture is both a carbon sink and a carbon source, and spetroleum carbon sequestration is the most cost-effective solution to achieving spetroleum health in a carbon-neutral way. Spetroleum carbon sequestration technology converts carbon dioxide into "spetroleum organic carbon", which is used to form biomass through corps and stored in spetroleum carbon pools, which can last for hundreds of years in ecosystems. In the attempt of spetroleum carbon sequestration, traditional tillage technology affects moisture content, leading to limited growth of crop root, and degrading spetroleum production and ecological functions. Therefore, applying organic fertilizer and using new cultivation technology can effectively improve spetroleum structure, increase spetroleum organic matter content, and enhance spetroleum carbon storage capacity. However, there is large error of the carbon dioxide content stored by this technology. Some studies suggest that the potential impact of spetroleum carbon sequestration has been overestimated by about 40% (Arehart et al., 2021).

It should be noted that the development of green technology and industry of carbon neutrality is still in the stage of research, development and demonstration, and there are still many constraints in the large-scale application and popularization. Among them, cost is the main obstacle to the development of CCUS technology. The research report of Goldman Sachs Group shows that natural carbon sinks are at the bottom of the carbon sequestration cost curve, and the cost of each ton of carbon dioxide sequestration is below $100. Among different carbon emission reduction technologies, the cost of capturing carbon dioxide from industrial point sources by CCUS varies greatly, depending on the concentration of carbon dioxide. The cost of biomass carbon capture and storage technology is between $100 and $250 per ton (Leonzio et al., 2020). Direct air carbon capture and storage is more expensive, with almost unlimited decarbonization potential and higher cost uncertainty. CCUS are relatively expensive, but they are an affordable option for countries or regions seeking to achieve carbon neutrality. In addition, from the perspective of technological development, carbon neutralization is not only a technical problem, but also a comprehensive problem of balanced economic and social development. Xinjiang and other regions of China have tired petroleum displacement method of carbon dioxide injection, but its economic benefits are still limited. The integration technology needs to be further studied, and the technical framework for the evaluation of storage security is inadequate. From the perspective of industry development, the existing CCUS projects are concentrated in coal chemical, petroleum enterprises, and carbon dioxide transportation, bioconversion and chemical synthesis are still in their infancy. At the same time, due to the geological characteristics of different regions, there are uncertainties in the potential and safety of storage, and the supporting safety management and monitoring system is not perfect. From the perspective of industrialization mechanism, cross-industry cooperation mechanism is not perfect in many countries. The huge industrial chain of CCUS covers many industries, such as steel, coal chemical, petroleum and gas, and electric power. Faced with challenges of matching and sharing of source and sink, ownership of intellectual property, responsibility sharing and risk sharing, long-term and effective industry norms as well as cooperation mechanisms need to be established to realize efficient interconnection of CCUS projects.

3. Actions and Trends of Global Carbon Neutrality

With the full implementation of the Paris Agreement, an increasing number of economies around the world have announced the goals of carbon peak and carbon neutrality, and have formulated strict carbon emission reduction measures according to the conditions of the region. However, there are large differences in policies and perceptions among economies, and carbon neutrality is facing imbalance and asymmetry. The politicization of climate issues in some economies has led to the deterioration of the global energy landscape and the rise of trade protectionism.

3.1 Developed Countries

Most developed countries have reached carbon peak and are actively promoting carbon neutrality, and most of them have defined the carbon neutrality schedule. As the most active group in promoting carbon emission reduction globally, there are significant differences within developed countries. The EU takes the lead in the carbon neutrality action, because the concepts of carbon peak and carbon neutrality originated in Europe, and the Paris Agreement was also initiated by Europe. Relatively speaking, the EU's carbon emission reduction efforts and the binding force of climate goals are stronger. In 2018, the European Commission proposed 2050 climate neutrality target in legislation, seeking to achieve the goal of becoming a climate neutral region by 2050. The most notable of these is the expected introduction of Carbon Border Adjustment Mechanism (CBAM) by 2023, which imposes tariffs on the EU imports, meaning that European manufacturers can avoid products in countries or regions with less stringent climate standards from entering the European market (Eicke et al., 2021). However, it will increase the product costs of enterprises within the EU. In 2019, the five Nordic countries said in Helsinki that they would jointly improve their efforts to tackle climate change and strive to achieve carbon neutrality faster. In the same year, the EU announced the "European Green Agreement", which plans to use clean energy, restore biodiversity, develop circular economy to achieve sustainable development, and achieve net-zero emissions by 2050. In 2020, the EU further confirmed the ambitious goal of establishing a "carbon-neutral continent". Although the impact of the energy crisis brought about by the Russia-Ukraine conflict continues, the EU will maintain a relatively positive position in the future. On the one hand, in June 2022, 120 countries or regions jointly pledged to accelerate the deployment of the most cost-effective methane emission reduction solutions in the fields of energy, agriculture and waste treatment, planning to reduce anthropogenic methane emissions by 30% in 2030 from the 2020 benchmark level, and marking the shift from consensus to action in methane emission reduction (Nan et al., 2021). On the other hand, the EU has decided to phase out coal with short-term pain. The gradual phasing out of fossil fuels and coal power plants in the power system is an important step in controlling the global temperature rise within 1.5 degree, and the “Powering Past Coal Alliance” joined by dozens of countries at the Glasgow Climate Change Conference is an important platform for achieving conversion of renewable energy (Blondeel et al., 2020). Furthermore, EU accelerates green recovery in all economic and social fields through climate action. The introduction of documents such as the European Green Agreement and the Glasgow Breakthrough Agenda not only outlines the medium to long-term blueprint for green development and digital transformation, but also provides scientific and technological solutions for achieving global climate change goals, which will have a significant impact on global industrial restructuring and economic landscape.

As one of the largest greenhouse gas emitters in the world, the US has actively adjusted its position on carbon neutrality and climate change. Since the Trump administration took office in 2017, significant reforms have been made to the climate policy of the previous Obama administration. In January 2017, Trump signed the America First Energy Plan, intended to revive the traditional coal industry, and increase employment opportunities in the US by lifting the ban on energy exploitation and relaxing the supervision on petroleum and gas development. In June, the US officially announced its withdrawal from the Paris Agreement, significantly reducing the budget for addressing climate change, which means that climate change with public goods attributes is difficult to balance with the rapidly developing economy (Selmi et al., 2021). On the contrary, the climate policy of the Biden administration has undergone a subversive adjustment, focusing on reversing the climate policy of the Trump administration, announcing a return to the Paris Agreement, vigorously supporting clean energy development, planning to achieve carbon-free power generation by 2035, and achieving the goal of carbon neutrality by 2050, indicating that the US plans to play a leading role in addressing global climate change (Olutola, 2020). At the political level, the Biden administration has incorporated climate change into national security strategy and foreign policy, eased multilateral climate diplomatic relations by promoting climate energy legislation, and promised to increase financial support for developing countries. At the economic level, the US has planned to invest $2 trillion in key areas such as clean energy research and development, infrastructure construction, and tax reductions for clean energy enterprises, accelerate the popularization of electric vehicles and renewable energy, and create millions of job opportunities in the carbon-free power sector. At the technological level, the ARPA-C energy policy has provided financial support for energy innovation, including carbon capture and storage, modular nuclear power, hydrogen energy, decarbonization processes, and planned to trigger a clean energy revolution in areas such as transportation, agriculture, and construction (Hu et al., 2020).

Although the goals set by the Biden administration are lower than the international community's expectations, they are still a significant step forward compared to the stance of the Trump administration. Therefore, whether the US can return to its leadership position in global climate change governance remains to be seen.

3.2 Developing Countries

Many developing countries are the main source of new global carbon emissions. Their carbon emissions are still in the climbing stage and have not yet reached the peak. The most important thing is to promote the early peak and rapid decline of carbon emissions. However, there is still a long distance between these countries and developed countries in terms of their awareness of climate change, level of economic development, process of energy transition, cost of capital and technical level of carbon neutrality. In the tide of global carbon neutrality, the goal of carbon neutrality proposed by these countries is met with many difficulties. In recent years, the position of developing economies has changed. India, Russia, the United Arab Emirates have actively participated in net-zero emissions of greenhouse gases and announced the schedule to achieve carbon neutrality.

As one of the G77 and BRICS countries, India has played an important role in the formulation and implementation of the United Nations Framework Convention on Climate Change. As a traditional agricultural country, India has a high vulnerability to climate change risks and is extremely vulnerable to the impact of climate change. Moreover, fishery and forestry, which are sensitive to climate change, are important industries that India depends on for survival, and they will have a significant impact on India's production and supply both in terms of time and space. With high poverty rate and high energy demand, the energy demand of India will account for 25% of global energy aggregate over the next 20 years (Thapar et al., 2016). Besides, the lack of trust of India in international negotiations is manifested in three aspects. Firstly, India does not believe that economic development is necessarily incompatible with the task of reducing carbon emissions, but attaches greater importance to synergies. Secondly, India has a more proactive image in international negotiations. Thirdly, India is expanding the use of renewable energy, especially nuclear energy and energy saving technologies. In general, although the mainstream voice in India believes that developing countries need to provide carbon emission space for economic development and should not make excessive demands in terms of technology and finance, the dual pressure at home and abroad has forced India to propose a carbon neutrality target by 2070, but it is not clear whether the underlying purpose of the pledge is to improve the contribution of greenhouse gas emissions or to meet the needs of diplomatic negotiations. India's future low-carbon transition still faces many practical constraints. For example, the economy which heavily dependent on coal is difficult to diversify and energy demand is still rising sharply, which makes it difficult for many residents who work closely with coal to accept the elimination of coal in a short time. Therefore, there is often a large gap between policy design and actual implementation, which is bound to affect the realization of carbon emission reduction targets.

According to IPCC, Southeast Asia is one of the world's most vulnerable regions to climate change, with many low-lying coastal cities and islands at risk from tropical cyclones and rising sea levels. Southeast Asian countries are seeking a scientific path to balance economic growth and carbon emission reduction. The carbon emission intensity and energy intensity of Vietnam, Myanmar have increased year by year, while Singapore and Malaysia have improved energy efficiency and reduced carbon emissions. To be more specific, Southeast Asian countries have divergent energy transition plans. Although most countries have made progress in submitting their intended Nationally Determined Contribution (NDC) targets on greenhouse gas emissions and formulating long-term climate strategies, they have yet to set clear road maps and binding emission reduction targets (Laudari et al., 2021). There is also a large gap between the more developed ASEAN countries such as Singapore in fulfilling their climate commitments. Additionally, there is a tendency among member states to seek leadership in Southeast Asia's energy transition, especially Indonesia and Singapore. The continuation of the past tradition of consultation and cooperation needs to consider bridging the planning differences between developed countries and developing countries in energy transition, which determines the future path of energy transition in Southeast Asia.

As a region with the highest forest coverage in the world and the most frequent deforestation, Latin America is at the forefront of carbon emission reduction among developing countries, and most Latin American countries regard carbon emission reduction as an important opportunity for national economic development. Colombia hopes to reduce greenhouse gas emissions by 51% in 2030, depending on the country's efforts to curb deforestation (Laverde-Rojas et al., 2021). Therefore, a climate governance path based on the concept of carbon sequestration can be achieved through forests, grasslands and wetlands. In contrast to carbon sequestration, Argentina should start at the source to reduce methane and short-term pollutants emissions, and call for the optimization of the international financial system and the implementation of environmental debt swaps through multilateral mechanisms, in order to reduce the economic pressure on less developed countries (Okere et al., 2021). In the long run, Latin American countries are undertaking large-scale deployment in the development and production of low hydrocarbon sectors, in order to replace fossil fuels that are not suitable for direct electrification. At the same time, they will create export opportunities for low-carbon products such as steel and ammonia. For the shortage of funds and insufficient technology, Inter-American Development Bank has committed 25% of its loans to clean energy and climate change, and China has also invested in financing clean energy installations. However, there are great differences in the positions and objectives of climate change among large economies, small and medium-sized economies and the Alliance of Small Island States in Latin America. Some countries also adjust their internal and external policies due to their internal political game and changes in political power. Due to the continued impact of COVID-19, the economies of Latin American countries have yet to fully recover, economic, social and political risks are increasing, policy implementation is not effective enough, energy reform and emission reduction actions may be put on hold.

3.3 International Organizations and Enterprises

Major international organizations in various fields around the world hold positive positions on carbon neutrality, including the International Monetary Fund, the World Trade Organization and the World Bank. The World Bank supports the long-term strategic goal of 2050 by launching a global tracking system with partners to change the opaque carbon credit market. Specifically, through climate financing, the World Bank uses financial tools such as green credit, green securities, green development funds, green insurance, and carbon financial products to help developing countries reduce financial risks in clean technology applications, increase market share in clean energy, and sell carbon credits to neutralize carbon emissions, helping polluters achieve net-zero emissions (Safi et al., 2021). According to the research report of the International Monetary Fund, in order to achieve the global temperature rise target, the world should complete 25%-50% of the carbon emission reduction task by 2030, and carbon pricing is the best means (Tozer & Klenk, 2018). The launch of the carbon emission verification and monitoring market will also help the operation of the carbon market.

In addition to international organizations, Amazon, Shell, DuPont and other well-known enterprises have also formulated carbon neutrality goals. Apple has operated in global companies to achieve carbon neutrality, and plans to use 100% clean energy power supply to support projects that will shift to clean energy business and promote climate solutions, so as to achieve carbon neutrality in the global supply chain and product life cycle. Large energy companies are building a clean and low-carbon diversified energy supply system by expanding their clean energy business and transforming into comprehensive energy companies. In addition, green finance can guide the flow of funds to resource saving technology development and ecological environment protection industries, guide enterprises to focus on green production and help consumers form a green consumption concept. As the world’s first life insurance company which issues green bonds, Canada Manulife Financial Group has participated in several international sustainable financial initiatives, taken sustainable economic transformation as an important factor affecting the long-term health and prosperity of enterprises, and committed to achieving carbon neutrality by 2050. The company’s green bond framework tracks the use and management of raised funds, disclosure of information report, and provides quantitative and qualitative environmental performance indicators for qualified green assets. Its carbon neutrality action plan will lead and demonstrate the industry and the overall economy. For major international companies, establishing, improving ESG investment management systems and encouraging the transformation of their business philosophy to green development is still in the initial exploration stage. The promotion and depth of green industry products and facilities in the future need to be further improved.

4. Realistic Dilemma of China’s Carbon Neutrality Goal

Firstly, China is far more difficult than developed countries to achieve the carbon neutrality goal. Most developed countries that have achieved carbon peak are naturally realized due to the completion of industrialization, urbanization and the change of industrial and energy structure. They have experienced a long period of multi peak, high level, platform fluctuation and nonlinear single peak. They have experienced a longer period of fluctuations with multi peaks, rather than non-linear single peak, while China's carbon neutrality goal of carbon peak is to actively commit to participate in global governance to deal with climate change. Hence, the pressure and task of carbon emission reduction is more arduous, which not only means that the cost of energy structure transformation is higher, but also ensuring energy supply is more difficult. Although China's energy structure is shifting from coal-based to diversified, and the development of renewable energy on the supply side is gradually shifting to areas with concentrated loads, coal remains an important guarantee of national energy security, and its proportion of carbon emissions from combustion is still close to 80%. In order to achieve the goal of carbon neutrality, China's consumption of non-fossil energy needs to reach about 25% by 2030 (Jie et al., 2021). The exit of fossil energy is a necessary way for China's low-carbon transformation. However, it is worth noting that in the context of zero-carbon renewable energy without perfect competition advantages, once the implementation speed of the hasty large-scale exit of fossil energy is too fast, it will face the risk of high energy prices, soaring inflation and even social unrest, which will interfere with the normal operation of the economy and society. In recent years, the large-scale power rationing phenomenon that has occurred in some provinces in China is closely related to the insufficient supply of coal-powered electricity. Therefore, coal will continue to be the largest energy source in China in the medium to long term, and the coordination difficulty between sustainable economic development and low-carbon energy transformation has significantly increased. The balance and synergy between industries need to be emphasized. In the new stage of development, the vitality of China's emerging markets needs to be further stimulated, and both the supply and demand sides need to undergo continuous reforms to assist in the comprehensive and sustainable transformation of economic and social development.

Secondly, the risks of low-carbon energy transition and energy security are increasing. The level of economic development and resource endowments in various regions of China are uneven, and their positions in the transformation of energy structure are different. If local energy policies cannot be promoted and keep pace with the country, insufficient implementation plans will be formulated, which will have an impact on social livelihoods and energy supply, and phenomena such as power outages and gas outages may occur again. At the current technological level of photovoltaic and wind power, large-scale grid connection requires sufficient peak shaving capacity and backup power, which will increase the additional economic burden on the grid and the intermittency of the power system. At the same time, the rapid development of energy digitization and intelligence has placed the energy industry at the center of cyber attacks, with a single vulnerability potentially exposing the entire supply chain, and with high-risk applications and vulnerabilities being the main threats. At the international level, China's petroleum and gas consumption mainly relies on imports, with a dependence on crude petroleum exceeding 70% (He et al., 2022). With further optimization of the energy structure and deep economic transformation, the demand for petroleum and natural gas will still remain at a high level in the future. In the short to medium term, China may face security risks in petroleum and gas supply. The turbulence in the energy market caused by international geopolitical competition and gaming will affect global energy supply, increase uncertainty in international energy trade and cooperation. Especially, the execution risks in payment and settlement will have far-reaching and long-term impacts.

Moreover, the development level and innovation driving force of key core technologies are still insufficient. To achieve carbon neutrality, it is necessary to transform the traditional energy system based on fossil energy established since the industrial revolution into a modern energy system based on clean energy, achieving net-zero emissions or even negative emissions. In order to achieve the goal of carbon neutrality, China has not mastered most of the key technologies in the transportation, power, steel, cement, chemical industry, construction, which are mainly embryonic technologies in the early stage of research and development. In addition, the application volume of low-carbon technology patents in various categories has a large growth rate and differentiation degree, focusing on transportation, sewage treatment, energy power generation, transmission and distribution, while patents in emerging fields such as CCUS technology, energy storage and green hydrogen technology are mainly practical rather than inventor patents. In the supply chain of the new energy industry, with the installation and coverage growth of wind power and photovoltaic, the reserves of key mineral resources such as lithium, cobalt, and nickel are insufficient. The core raw materials such as rare earth elements and rare metals required for the popularization of renewable energy will face shortages. Without new recycling technologies and new alternative materials, it may hinder the large-scale application of renewable energy. From the point of view of the market, the technological policy support in the early application stage is insufficient, the evaluation system is not sound, the market demand is weak, and all parties have low awareness and understanding of green technology, as well as social participation, among them the key technologies in the early application stage require dual stimulation from the policy and market side. In addition, the green project evaluation does not fully balance economic benefits, industrial development, and environmental factors, resulting in resource waste throughout the entire life cycle of the technology. Mature technologies also face the phenomenon of "midrange technology lock-in", and it is difficult to support the development and breakthrough of core technologies by exchanging technology with the market.

Finally, the carbon neutrality process faces a huge funding gap challenge. The commitment of carbon neutrality marks the beginning of a new wave of China's green revolution. To achieve the goal of carbon neutrality by 2060, China is expected to need about 140 trillion RMB of green financing in transportation, power, construction, real estate (Zhou et al., 2020). The construction industry and manufacturing industry are the main sectors contributing to China's GDP. If China wants to achieve net zero emissions, it needs a lot of money to invest in technological progress and financial innovation. Compared to other economies, the Chinese government budget can only meet some of the demand, and it is necessary to encourage public and private sector investment funds through market-oriented means. In addition, the core of Chinese enterprise financing is bank loans, but the mortgage requirements are too strict, the loan cycle is insufficient, the pricing mechanism is rigid, and the mismatch between transaction structure, financing tools, term structure has led to the main flow of funds to large enterprises. As the main source of carbon emissions, small and medium-sized enterprises are hindered in obtaining financial support. At the level of financial innovation, green finance and carbon emission trading can make up for the funding gap. The carbon market can solve the problem of large-scale, low-cost, and long-term funding shortage in the development of new energy. However, at present, for green finance, there are problems to be solved, including small pilot scale, high financing costs, shortage of long-term green credit and equity green financing.

5. Systematic Carbon Neutrality Solution Framework Supporting China's Sustainable Development

5.1 Accelerate the Construction of Modern Energy System

Since the 13th Five Year Plan period, China has accelerated the pace of clean and low-carbon transformation, with the installed proportion of non-fossil fuels increasing to 47%. The scale of energy production and consumption system ranks first in the world, but there is still a significant gap in energy consumption intensity per capita compared to developed countries. The construction of a modern energy system is the key to achieving carbon peak and carbon neutrality. Therefore, it is necessary to adjust the energy structure dominated by fossil energy to the energy structure dominated by clean energy, and let the development of non-fossil energy and re-electrification gradually replace the stock of coal and petroleum, so as to promote the coordination and complementarity of new energy and coal power. Adhering to the sustainable, clean, efficient development and utilization of coal is of utmost importance, however, the current distribution of energy resources is uneven. The overall distribution of energy shows a pattern of more in the west and less in the east, and more in the north and less in the south. Major projects such as the West to East Gas Transmission and West to East Power Transmission cannot completely change the current situation of energy shortage in the central and eastern regions. The development level of local distributed new energy, offshore wind power, coastal nuclear power in the central and eastern regions is insufficient, and the system planning between different regions needs further improvement. On the one hand, China needs to accelerate the establishment and improvement of energy production, supply, storage, and sales systems, accelerate the construction of cross-regional transmission networks for petroleum, gas, and electricity, strengthen the construction of natural gas storage facilities, optimize regional energy structure, and enhance the elasticity of energy supply capacity. On the other hand, China needs to optimize the early warning mechanism for energy supply and demand, and improve the ability to respond and restore energy supply quickly. In addition, China's energy structure, which currently relies heavily on coal and petroleum, should moderately develop projects such as coal to petroleum and coal to gas. On the premise of ensuring safety and economy, China can actively develop ultra-high voltage transmission, build and match a reasonable and well-defined smart grid, and improve the level of clean energy consumption in the grid.

5.2 Enhance Independent Innovation Capabilities in Science and Technology of Energy System

The important symbol of the fourth industrial revolution is the evolution of energy technology, which not only decouples carbon emissions from economic growth, but also effectively improves green energy efficiency, making it a strategic driving force for future economic growth. The main characteristics of the new round of technological and industrial revolutions are the continuous emergence of major disruptive technologies and the accelerated transformation of scientific and technological achievements. The improvement of China's independent innovation ability in energy technology and the level of equipment localization need to be compared to the international advanced level. In terms of petroleum and gas exploration, development and utilization, cutting-edge technologies such as high-precision intelligent fracturing technology, need to be vigorously addressed to enhance risk resistance capabilities. The nuclear power industry, which started relatively late, has the advantage of latecomers. Basic scientific and technological issues, including advanced nuclear energy development need to be solved, and the efficiency of converting the total installed capacity of nuclear power into total power generation needs to be improved. The scientific research of special materials, safety equipment, and control systems urgently need to be overcome. For hydrogen energy technology, China has not yet formed a complete hydrogen industry technology innovation system, clean energy hydrogen production and supply system. Once the key technology of hydrogen energy gets breakthrough, it will continuously expand new market application space and guide the high-quality development of the industry. Similarly, cutting-edge development trends such as high-performance energy storage batteries and solar energy technology are gradually moving towards low-cost, intelligent, decentralized and clean. Energy digital technology will become the source of leading global energy industry transformation and achieving sustainable innovative development. Specifically, the large-scale application of digital technology will reduce petroleum and gas production costs by 10%-20%, and increase global petroleum and gas recoverable reserves by 5% (Wang et al., 2023). Therefore, China needs to accelerate the deep integration of modern information technology and the energy industry, promote the digitization of energy infrastructure, build application scenarios and industrial models based on 5G and other technologies, and promote the transformation of energy system through pilot demonstrations, reshaping the energy future.

5.3 Improve Carbon Emissions Trading Market

The carbon emissions trading market is an important market-oriented emission reduction tool. In 2021, China's national carbon emissions trading market officially launched. As the world's largest carbon emissions trading market, there are still some mechanism issues in the initial pilot work. First of all, the pilot provinces and cities are geographically dispersed and operate independently, making it difficult to form a scale effect. The temporary measures introduced by each pilot are inconsistent with the identification standards for enterprises included in the scope. Secondly, it emphases the secondary market over the primary market, failing to balance fairness and efficiency in the initial allocation of carbon quotas. Thirdly, the supply of products of carbon emission rights is relatively single, and the liquidity is lower than that of EU ETS carbon market. Besides, the regulatory authorities' understanding of the carbon emissions trading market needs to be improved, and they attach too much importance to risk avoidance, without conducting futures trading, and the enthusiasm of various entities to participate is limited. The carbon emissions trading market and carbon finance market need to be supported by sound and continuous policies, establish clear dynamic adjustment mechanisms, gradually expand industry coverage, and collaborate with multiple parties to promote the standardized and low-risk development. In terms of international cooperation, green low-carbon markets and green technology innovation processes can be promoted in countries along the "the Belt and Road" through green funds and other means, effectively combining the carbon market with climate change, promoting ESG investment, and helping to achieve the SGDs. Since the new round of power system reform, the role of the market in the optimal allocation of resources has significantly improved. Improving energy production and supply capacity, accelerating the construction of a unified national power market system, and promoting the participation of new energy storage in spot market transactions will contribute to the development direction of solar thermal energy storage in the future. Building a broader power market is the general trend of power market reform. At the initial stage, China's unified power market pilot mainly refers to the development model of the US power market, and later gradually refers to the European power market. To reduce the impact of the uncertainty and volatility of renewable energy on the power system, the power system needs to enhance the supply of flexibility and reliability services to meet the demand for a high proportion of renewable energy integration into the power system. A unified national electricity market also contributes to the transformation of low-cost electricity energy and technological innovation, broadening the boundaries for the development of renewable energy.

5.4 Accelerate the Optimization and Upgrading of the Entire Industrial Chain

The optimization and upgrading of the entire industrial chain requires accelerating the green, intelligent, and high-end development of traditional industries. At present, the Chinese power sector is unable to fully absorb zero-carbon electricity, and local area network technology and distributed technology have not yet been widely popularized in the market. Therefore, zero-carbon solutions cannot be unilaterally emphasized, nor can they be developed through deforestation. The development of physical energy storage, chemical energy storage, complementary solar and solar energy, and biomass energy in China needs further attention. By 2021, the installed capacity of China's energy storage market has reached 43GW, with broad development prospects, especially in the commercialization of electrochemical energy storage (Ji & Zhang, 2019). If the production costs and device cycle life are scaled up, it can promote the large-scale and high-quality application of clean energy. In addition, the hydrogen energy industry chain will play an important role in carbon neutrality. However, the current industrial planning and layout are not reasonable enough, and there are more redundant and backward production capacity. It will take some time for green hydrogen preparation projects and intelligent equipment manufacturing to become large-scale and market-oriented. From the demand side, the overall demand of the industry will continue to increase. From the supply side, the chemical industry's production of raw materials is highly dependent on coal, and the risk of asset stranding is also high. At the same time, a strong level of technological integration and the trend of industrial scale integration will bring more opportunities. In the context of zero-carbon emissions, the high-end production of synthetic ammonia, methanol, ethylene, as well as the optimization of low-end production capacity, will achieve substitution shift. The Power-to-X distributed mode and large base mode based on green hydrogen can serve as comprehensive solutions, forcing outdated production capacity elimination and industrial upgrading and innovation. The competition of new energy vehicle industry in China is becoming increasingly fierce, and due to the impact of marginal diminishing effects, it is gradually shifting from rapid development to steady development. Subsidies will not change the long-term trend of improvement, and there is still room for improvement in future demand and industrial investment value. The growth potential of strategic industries remains strong, including microgrids, local area networks, and biopharmaceuticals, with emerging momentum remaining active and competitive advantages continuously accumulating, making them a cutting-edge strategic growth pole for the future.

5.5 Cultivate Public Awareness of Low-Carbon Consumption

Achieving zero-carbon transformation requires not only a subversive technological revolution, but also a change in the concept of the whole society. China is still and will remain a developing country for a long time, and consumption plays a fundamental role in both quantity and quality in economic development. Therefore, the outdated economic development concept led by GDP in some regions needs to be completely changed. Encouraging clean and low-carbon consumption means lower energy consumption and less carbon emissions, of which technological progress and energy system efficiency improvement will be offset by increased consumption, while the greenhouse gas emissions generated by China's household consumption account for about 50%, and this figure will continue to rise with the improvement of quality of life, so low-carbon consumption reform has great potential in the carbon neutrality field. In the carbon emission structure, 26% of the energy consumption used for people's life accounts for more than 30% of the carbon emissions. To promote carbon neutrality, efforts must be made from both the supply side and the demand side to foster public awareness of low-carbon consumption. Consumption behavior dominates market supply and demand, and consumers' weak subjective environmental awareness makes low-carbon practice less subjective. Therefore, to achieve carbon neutrality, it is necessary to cultivate consumers' low-carbon cognitive ability to improve their understanding of the connotation of carbon neutrality, guide consumers to change their consumption patterns and improve their willingness, so as to pay for low-carbon goods and carbon costs through policy tools. For the consumption side, measures with carbon emission reduction efficiency, strong acceptance and operability need to be selected in policy design, including conducting a systematic evaluation of citizens' green and low-carbon behavior, incorporating consumption carbon emissions into national carbon emission reduction responsibilities, and emphasizing on spatial planning and the matching degree between urban areas and consumption mode transformation, providing possibilities for low-carbon living and low-carbon travel. For the demand side, policy formulation needs to prioritize the improvement of fairness and well-being, encourage the participation of diverse entities, incorporate consumer behavior into the framework of social practice, attach importance to the diversified nature of social practice and its important correlation with the supply system, and leverage green changes on the supply side through the demand of low-carbon consumption.

6. Policy Recommendations

Firstly, China needs to strengthen top-level design and steadily promote low-carbon transformation. Achieving carbon neutrality is an extensive and profound economic and social systematic change, which requires all parties to control carbon emission reduction efforts to avoid the occurrence of energy supply risks. Policy formulation needs to be carried out in stages and steps, taking into account the needs of short-term economic recovery, medium-term structural adjustment, and long-term development transformation. China needs to minimize coal production and consumption as much as possible, and pilot coal-free cities can be established in major cities to reduce direct demand of coal consumption. The approval criteria for major investment projects in the coal industry need to be tightened, reducing the provision of new fixed asset loans during the process of reducing production capacity, and timely launching restriction and reduction plans of coal production. For industries with high pollution and carbon emissions, it is necessary to formulate structural green reform plans in advance to achieve a significant transformation from high carbon to carbon-free development. In addition, policy formulation needs to adapt to different stages of technological development. For strategic and forward-looking prototype technologies, the government should vigorously promote energy conservation and efficiency improvement. For innovative technologies in the development and early experimental stages, China should respect the laws of industrialization of scientific and technological achievements, create a satisfying innovation environment, and lay a solid foundation for technological industrialization. For mature technologies that have entered the stage of market promotion and application, policy innovation should be used to address potential obstacles to market operation, ensuring that they meet the needs of economic and social development in a safe, reliable, and economically feasible manner.

Secondly, China needs to improve the guarantee mechanism to ensure energy security. The government needs to clarify the long-term development roadmap for zero-carbon and negative carbon emission technologies such as green hydrogen energy, and mobilize social forces to strengthen technology research and demonstration applications. Although the cost of zero-carbon energy has significantly decreased in recent years and there is a possibility of large-scale development, scientific policy design is needed to create market space for it. This can mainly be achieved by improving market-oriented emission reduction policies, including carbon emission trading mechanisms and carbon tax systems, to enhance the market advantage of applications for zero-carbon energy technology. It can not only reduce enterprise costs, but bring further benefits of zero-carbon energy technology applications to the market and private return. Ensuring the security of financial markets is equally important, and it is necessary to ensure the synergy between innovative policies and financial market tools. In the context of the construction of the green finance system and the carbon emissions trading market, it is necessary to promote the establishment and updating of technical standards for decarbonization, zero-carbon and negative emissions, require all listed companies to disclose carbon emissions and carbon trading information, gradually impose carbon taxes on large enterprises. In addition, in response to the crisis response mechanism, it is necessary to improve the energy reserve system with regulatory functions, enhance the ability to ensure energy security, and establish an energy supply and demand early warning mechanism to enhance the system's rapid response and recovery capabilities.

Thirdly, China needs to enhance the core competitiveness of the industrial chain. In terms of basic research, it is necessary to increase the investment of the government and all parties of society in applied research. For sectors with high carbon emission reduction costs such as transportation and industry, deep carbon emission reduction can be promoted through the development of BECCS, gas power CCS and coal power CCS technologies. At the same time, direct air carbon capture technology can be actively developed to reduce the cost of energy carbon neutrality at the full economic scale, laying a technical foundation for achieving carbon neutrality. For disruptive carbon emission reduction and carbon sequestration technologies with long research cycles, innovation should be the driving force for upgrading and innovating the industrial chain, promoting the development of industries towards low-carbon. In terms of key core technologies, it is necessary to encourage eligible enterprises for market-oriented transformation of scientific and technological achievements, concentrate financial resources to cultivate modern high-tech industrial clusters with development potential, and build a group of benchmark enterprises that can lead the development of the industry through scale expansion, mergers and acquisitions, and restructuring.

Fourthly, China needs to strengthen the support of innovative talents. It is important to establish a talent support system that adapts to the strategic system of the new era, coordinate the reform of talent policy system, and ensure that the construction of high-level talent teams continues to achieve outstanding results. At the national level, it is necessary to increase investment and incentive measures for green and innovative small and medium-sized enterprises, and encourage study and exchange among various industries. At the enterprise level, it is necessary to deepen the integration of production, education, and research, and attach importance to the cultivation and appointment of technical personnel and high-end talents. At the same time, international scientific and technological talents can be appropriately introduced. A high-level talent recruitment, salary, evaluation, assessment, scientific research funding and management system that is in line with international standards can be established, and the research and development of low-carbon environmental protection technologies can be accelerated to lay a good technical foundation for achieving carbon neutrality. In addition, it is necessary to support enterprises, universities, and research institutes to participate in the formulation of international standards for strategic emerging industries and their segmented fields.

Achieving the carbon neutrality goal is a process of multi-objective optimization and dynamic balance, while China's carbon peak and carbon neutrality goals are urgent in time and significant in task, which undoubtedly faces many challenges. As the world's largest developing economy, China's role in global climate governance is gradually changing. The realization of carbon peak and carbon neutrality goals will help provide solutions for low-carbon economic development in other countries.

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