Exploring the Path of China's Energy Transformation under the "Carbon Peaking & Carbon Neutrality" Goals

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Abstract. The key to achieving peak carbon emissions and carbon neutrality lies in the low-carbon transformation of energy and power, which is crucial to China's overall economic and social development. With the intensification of global climate change, countries are actively exploring strategies to adapt to climate change. However, coal, as the main future energy source, is expected to remain dominant, making it urgent to advance the transformation of fossil energy towards low-carbonization. In this context, this paper comprehensively analyzes the timing of the reduction of fossil energy and the replacement of non-fossil energy in China through a comparative analysis of the international and domestic energy transformation status, taking into account the need to ensure energy supply security and achieve China's economic and social development goals. The paper proposes development suggestions for China's energy development path, including optimizing and upgrading the industrial structure, building a clean and low-carbon energy system, strengthening CCUS technology development, and leveraging market mechanisms. These recommendations provide a certain reference and guidance for China to achieve its energy transformation goals.

1 Introduction

Advancing the "carbon peaking & carbon neutrality" target has become one of the major national strategies, which is not only a solemn commitment to the international community, but also a reflection of the inherent requirements of high-quality development.China has preliminarily established a "three-step" target framework led by the national administrative authorities, with the market as the main body and enterprises as the responsible parties.Opinions on fully implementing the new development concept and doing well in achieving peak carbon dioxide emissions and carbon neutrality (2021) states that we should accelerate the comprehensive green transformation of economic and social development and the construction of a clean, low-carbon, safe, and efficient energy system[1].Under the "carbon peaking & carbon neutrality" target, China's energy structure is facing enormous adjustment pressure. Energy, as an important element throughout the entire process and various aspects of economic and social development, plays a crucial role in achieving the "carbon peaking & carbon neutrality" strategic goal. China's economy has entered the era of low-carbon development, and deep reforms are needed in energy production, consumption, and other areas. The promotion of energy transformation, the realization of decarbonization and zero-carbonization of electricity, fuel and other energy sources, improving the efficiency of energy demand side, promoting the electrification and intelligent utilization of energy, and constructing a modern energy system dominated by new energy sources, combined with fossil energy + carbon capture, utilization and storage (CCUS) and nuclear energy as protection strategies are necessary. This will demonstrate the characteristics of "clean, low-carbon, safe, and efficient" to support the achievement of the "carbon peaking & carbon neutrality" strategic goal[2].

In the field of foreign research, HEL et al. [3] proposed three target scenarios and used the CHINAGEM dynamic general equilibrium model to explore the impact of different energy pathways on the economy and environment under long-term low-carbon transformation. ZHOU S et al. [4] used the Global Change Assessment Model (GCAM) to explore the path for China to achieve energy supply and low-carbon transformation from three scenarios. CHUN YT et al. [5] used the 3E model to construct a set of carbon neutrality evaluation indicators and studied the path for improving carbon neutrality capabilities in each province of China. WANG B et al. [6] used an improved LEAP model to predict and analyze the thermal power generation and installed capacity for the years 2025 and 2030 under normal and extreme weather conditions. ZHAO GP et al. [7] constructed a bottom-up linear optimization model C3IAM/NET based on the 2° C climate target, revealing the energy consumption, carbon emissions, and technology pathways at the national and sectoral levels.

In the field of domestic research, Huang Zhen et al. [8] conducted a thorough analysis of the current status of China's energy development and predicted and analyzed the future medium- and long-term energy demand and

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transformation trends in China. Based on electricity carbon budget evaluation, Shu Yinbiao et al. [9] constructed three electricity transformation scenarios and proposed the path for low-carbon transformation of electricity under different scenarios. Luo Shihua et al. [10] proposed a carbon-neutral energy system planning method based on a comprehensive energy system, exploring the possibility of achieving China's carbon-neutral goals and the required technology support and cost requirements. Wei Hongyi et al. [11] proposed an extension planning model for the power grid system, aiming to plan the "carbon peaking & carbon neutrality" transformation path of China's power system. Wei Yiming et al. [12] proposed a national energy technology model that comprehensively considers economic benefits and safety to achieve sustainable energy utilization. Based on the research method of key industry/sector carbon peak path, Cai Bofeng et al. [13] and Yan Gang et al. [14] analyzed the carbon emission peak path of key energy-consuming industries by using social and economic development demand and carbon peak targets as macro constraints.

In summary, extensive research has been conducted on the future development trends of China's energy system. The carbon-neutral transformation of the energy system is an urgent, arduous, and complex process that requires comprehensive consideration of various aspects of development and emissions reduction. In this process, we need to balance the relationship between economic development and carbon reduction, and promote the development of green and low-carbon alternative energy sources as soon as possible to achieve the decoupling of economic development and carbon emissions. This is a systemic engineering project that requires the comprehensive use of various means and strategies, including technological innovation, policy guidance, and market mechanisms, to promote the smooth progress of energy transformation, achieve sustainable economic development while reducing carbon emissions, and contribute to building a cleaner and sustainable energy future.

In the process of achieving the "carbon peaking & carbon neutrality" goal, in-depth exploration of China's energy transition path is a necessary prerequisite and foundation for designing the energy transition path. Therefore, corresponding research is particularly urgent. This article systematically summarizes and generalizes the current situation of global and China's energy transition, structural transformation, transition path, and other aspects, providing a reference for the follow-up research of China's energy transition.

2 The current situation of global energy transition

2.1. A historical shift in energy consumption structure

In 2021, as the global economy began to recover from the COVID-19 pandemic, the energy system showed a strong rebound. Global energy demand and carbon emissions have roughly returned to pre-pandemic levels, reversing the brief downturn in 2020. Over the past decade, global primary energy consumption has remained stable overall, with peak oil equivalent reaching 14,101.0 million tons in 2019. However, due to the impact of the pandemic, oil consumption declined by 4.7% in 2020 to 13,442[15].1 million tons of oil equivalent. In terms of the structure of global primary energy consumption, although oil remains the largest component of the global energy mix, its share has decreased. As of 2020, it accounted for 31.2% of global primary energy consumption. Coal remains the second largest source of energy globally, accounting for 27.2%. At the same time, the share of natural gas is steadily increasing and has now risen to 24.7%. Nuclear power has been replaced by renewable energy, with its share reaching 5.7%. As shown in Fig 1, from 2010 to 2020, China's primary energy consumption continued to grow, the US's primary energy consumption continued to fluctuate but generally stabilized, and the EU's primary energy consumption showed a downward trend. From a global perspective, as fossil fuels are gradually depleted, new energy sources are becoming the main engine of energy demand growth. Compared to last year, hydropower has increased its share in energy consumption by 0.4 percentage points, reaching 6.9%. China's dependence on fossil fuels for economic growth is decreasing year by year. Fossil fuels have maintained their dominant position in global energy consumption, accounting for as high as 83.1% as of 2020[15]. However, as the share of clean energy continues to increase, energy consumption is showing a significant trend towards low-carbon transformation.

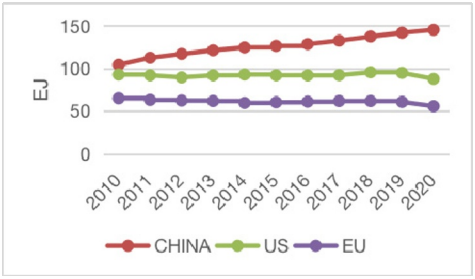

Fig. 1. Primary energy Structure of China, the US and the EU from 2010 to 2020
Source: BP World energy resources Statistical Yearbook(2021).

2.2 Changes in Power Structure

Electricity plays a critically important role in the entire energy consumption structure, serving as a necessary cornerstone of human production and living. With the rapid development of China's economy and society, the disappearance of population dividends, and the intensified global climate change, electricity demands have been increasing year by year. In the future energy pattern, electricity will play an even more significant role, particularly in achieving the "carbon peaking & carbon neutrality" target. As shown in Fig 2, from 2010 to 2020, the continuous growth of China's power generation reflects its rapid economic development and growing energy demand.The overall stability of electricity generation in the United States may benefit

from improvements in energy efficiency and the impact of energy transition policies. The decline in electricity generation in the European Union may be helped by its efforts to reduce carbon emissions and promote sustainable energy development.

The sustainability and stability of electricity supply and storage will directly impact the regional economic development process. Fossil fuels, renewable energy, and nuclear power generation are the main sources of electricity. Currently, over half of the world's electricity comes from fossil fuels. In the past decade, fossil fuel power generation still dominated global energy generation, primarily in the form of coal-fired power generation and followed by natural gas power generation. As the human demand for energy increases with economic growth and chemical and stone resources become scarce, finding alternative energy sources has become one of the important issues of global concern. In 2020, fossil fuel power generation accounted for 61.3% of the world's total power generation, while the proportion of natural gas as a clean energy increased by 1.5% to 23.4%[15].With the continuous progress of new energy generation technologies, wind power and photovoltaic power generation have been increasing year by year, and nuclear power has also seen rapid development. With the vigorous development of renewable energy technologies, the costs of wind power, solar power, and other power generation technologies have been effectively reduced. The global proportion of renewable energy generation has climbed to 28.6% in 2020, an increase of 8.5% from 2011. At the same time, with the gradual deepening of power market reform, the competition level of the power market is becoming increasingly high. In the past decade, the proportion of coal-fired power generation has experienced a significant decrease from 41.1% to 35.1%, a decline of 6%[15]. This means that the global energy structure will undergo significant changes in the future, and the traditional coal-dominated power generation will face enormous challenges, while new energy generation has good development prospects. However, coal-fired power generation still remains the main power generation method globally and its position in the energy sector is unshakable. With the depletion of fossil fuels and the increasingly severe issue of greenhouse gas emissions, the concept of "carbon peaking & carbon neutrality" has emerged as an important challenge that we must face and solve.

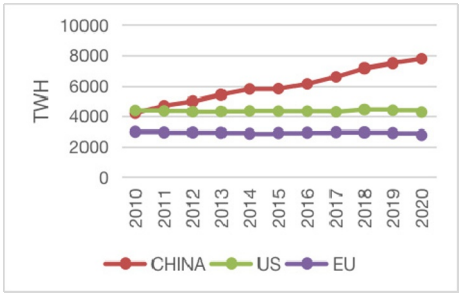

Fig. 2. Trends in electricity generation in China, the US, and EU from 2010 to 2020
Source: BP World energy resources Statistical Yearbook(2021).

3 The Current Situation of Energy Transformation in China

3.1 Transformation of Historical Consumption Structure of Primary Energy

As of 2020, the total primary energy consumption in China has reached 3,512.8 million tons of oil equivalent, accounting for 26.1% of the global energy consumption [16]. The proportion of fossil energy in China's primary energy consumption has declined from 92.0% in 2011 to 84.3% in 2020. Due to the increasing demand for energy caused by the rising international oil prices and economic development, the consumption of fossil energy in China has been growing over the years. Compared to the global level (83.1%), the United States (81.7%), and Japan (87.0%), China's energy consumption structure in 2020 remained relatively steady, slightly higher than Germany (75.6%)[16]. At present, China is in the middle stage of industrialization, and coal is still the dominant energy source. As shown in Fig 3, the proportion of coal consumption in China's total energy consumption in 2020 is 56.6%, which is several times the level of the United States (10.5%) and the European Union (10.60%). Therefore, coal is still the main energy demand in my country at present. Natural gas, as a cleaner energy source, only accounted for 8.2% of China's energy consumption in 2020, though it has increased compared with 2011, it still lags behind the levels in the United States, Japan, and Germany.

In the past decade, the proportion of renewable energy consumption in China has doubled from 1.0% to 5.4%. Although it still lags behind Germany (18.2%), it has approached the global average level (5.7%)[16].

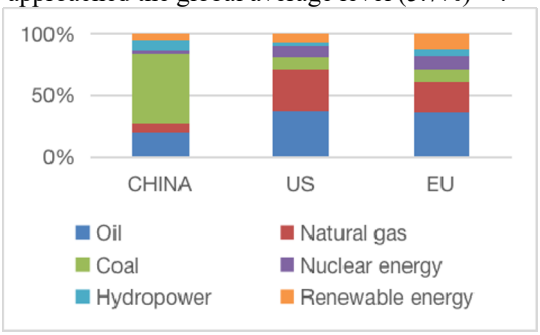

Fig. 3. Primary energy Structure of China, the US and the EU in 2020.
Source: BP World energy resources Statistical Yearbook(2021).

3.2 Changes in the power structure

In the field of power, China is also actively promoting energy transformation. In recent years, there have been certain changes in the development of China's electricity. With the increasing maturity of renewable energy generation technologies, various forms of renewable energy generation, including wind and solar power, have gradually increased their proportion in China's power structure. As shown in Fig 4, renewable energy generation accounted for 28.2% of China's total electricity generation in 2020, and its growth rate

reaches 13.8%[16]. from 2011. At the same time, the proportion of coal-fired power generation has gradually decreased. To cope with environmental pollution and carbon emissions, China has gradually reduced the proportion of coal-fired power generation. In the past decade, the proportion of coal-fired power generation in China's power structure has declined from 72.6% in 2011 to 57.7% in 2020, a decrease of 14.9%[16]. Hydroelectric and nuclear power generation have maintained a relatively stable trend and are important components of China's power structure. In recent years, the proportion of hydropower generation and nuclear power generation in China's total electricity generation has remained relatively stable, accounting for 15.9% and 4.8%[16]., respectively. Overall, China's energy transformation has made some progress. The proportion of fossil energy in primary energy consumption has decreased, and the proportion of renewable energy generation continues to increase. However, coal is still the main source of energy consumption and power generation in China. To achieve the "carbon peaking & carbon neutrality" goal, it is necessary to further reduce the proportion of coal-fired power generation, increase the proportion of clean energy, and promote the development of a diverse and low-carbon power structure.

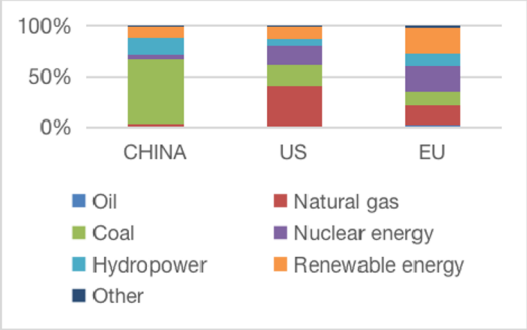

Fig. 4. Power Structure of China, the US, and the EU in 2020. Source: BP World energy resources Statistical Yearbook(2021).

3.3 Analysis of Energy Transition Pathways

In 2015, the Paris Agreement was adopted, which requires countries to actively promote Low Emissions Development Strategies (LTS)[17]. China has proposed to accelerate green and low-carbon development, but different countries have diverse energy transition pathways due to differences in resources, policies, and economies. The United States is implementing an energy transition plan that integrates non-fossil and fossil energy to achieve sustainable development. With abundant fossil fuel resources, the US is promoting renewable energy such as nuclear, wind, and solar energy to promote global sustainable development [18]. The European Union is committed to energy electrification transformation to adapt to changing energy demands. Due to scarce fossil energy, the EU is actively promoting renewable energy and advocating for low-carbon and clean energy transition, making energy electrification the core of its overall actions [19]. Japan adopts a diversified energy strategy, having ceased using nuclear energy due to the Fukushima nuclear accident. Instead, Japan uses other sources such as thermal power, wind power, and photovoltaics, and encourages investment and development of new energy. Japan has released its "Basic Energy Plan," which includes coal, nuclear power, natural gas, and oil as main energy sources and aims to achieve diversified energy structure transformation by 2030 [20]. Despite developed countries such as the US, EU, and Japan developing low-emission development strategies suitable for their respective countries, energy transition policies dominated by fossil fuels bring carbon emission risks to achieving global "zero-carbon" emission targets.

As China's economy and population grow, energy demand is increasing rapidly. China mainly relies on coal, but oil and gas resources are relatively scarce. Achieving energy transition is a challenging task that requires exploring a path suitable for China's national conditions. China should promote the efficient and clean use of coal, actively develop renewable energy such as natural gas, nuclear, wind, and solar energy, and strengthen the development and utilization of traditional fossil fuels to optimize the energy structure. China has now introduced relevant policy measures to encourage the development and utilization of clean energy, support renewable energy, and enhance international cooperation, actively participating in global climate change affairs and contributing to sustainable development.

4 The severe challenges faced by energy transformation

4.1 The deadline for carbon neutrality and the task of green and low-carbon transformation are daunting

Developed countries have naturally achieved the peak of carbon emissions through structural upgrades and technological advances, slowly declining after a plateau period. European and American countries have pledged to remain between carbon peak and carbon neutrality for 50 to 70 years. China faces a severe situation of carbon dioxide emissions in the future. Currently, China's per capita GDP has exceeded the threshold of $10,000. By 2035, China's per capita GDP is expected to reach the level of a moderately developed country[8]. In order to maintain a relatively fast economic growth, CO2 emissions will continue to increase under favorable conditions. To cope with climate change, it is necessary to reduce greenhouse gas concentration and emissions. The goal is to achieve decoupling of carbon emissions and economic growth within 30 years after 2030, and gradually achieve carbon neutrality by 2060. The transformation period will be shorter, but it will face enormous challenges. China needs to take unprecedented measures to accelerate green and low-carbon transformation. Traditional high energy consumption, high consumption, and low value-added industries will find it difficult to adapt to the new situation. As the biggest energy consumer and carbon emitter, China must take action to achieve the goal of carbon neutrality.

4.2 The task of optimizing and upgrading industrial structure is extremely challenging

The secondary industry in China accounts for more than 40% of GDP, and heavy industry is the economic backbone, but it is also one of the sectors with the highest energy consumption. The energy consumption required per unit of output is four times that of other industries. As the economic structure is being upgraded, the industrial structure is being adjusted, but high energy-consuming industries such as steel, non-ferrous metals, building materials, petrochemicals, and chemicals still account for 85% of manufacturing energy consumption. The slow upgrading of the industrial structure results in low energy utilization efficiency and high energy consumption of industrial added value. The output of heavy industries such as crude steel, coal, cement, and automobiles is high, so reducing energy consumption is crucial. China's manufacturing value chain is shifting towards high-end products, but it still undertakes energy and resource-intensive manufacturing, resulting in high unit GDP carbon emissions. China's trade imbalance exacerbates environmental problems. China exports a large number of industrial products to developed countries, causing carbon emissions transfer. The international trade and division of labor pattern are difficult to change, posing challenges to China's control of carbon emissions.

4.3 The situation for energy structure, which is biased towards coal and needs optimization, is grim

As one of the countries that relies mainly on coal as its energy source, China has a huge demand for energy, and coal consumption continues to increase. Coal accounts for as high as 56.8% of the total energy consumption, while non-fossil fuel has a relatively low share. China's per-unit energy consumption of secondary CO2 emissions is relatively high, and coal's carbon emissions are 36% and 61% higher than those of oil and natural gas, respectively. China's carbon emissions in the energy sector account for 77% of the total national emissions and 28.8% of the global emissions from fossil fuel combustion[21]. With the continuous increase in demand for energy due to economic development and improved living standards, it is expected that coal consumption will continue to rise in the future. The dominance of coal in China's energy structure is difficult to change rapidly, posing a huge challenge to achieving low-carbon transformation of energy. Against the background of enhanced environmental awareness, the concept of low-carbon living has become a consensus. China needs to take measures to reduce coal consumption and carbon emissions in order to achieve sustainable development and environmental protection.

4.4 The mission to improve energy utilization efficiency is extremely arduous

China's energy utilization efficiency is relatively low, with energy consumption intensity and carbon emission intensity higher than the average level of industrialized countries, requiring strengthened sustainable development. Improving energy utilization efficiency can reduce energy consumption and carbon dioxide emissions. Although China has been one of the countries with the fastest increase in global energy efficiency in the past, with a decline rate in energy consumption intensity far exceeding the global average, it still lags behind the world's leading level. China's energy consumption intensity is 1.8 times higher than the global average, and carbon emission density is also rapidly decreasing. However, China's energy structure is biased towards coal and energy utilization efficiency is low, leading to significantly higher carbon emission intensity than the global average. Therefore, China needs to optimize its energy structure, construct a sustainable, environmentally-friendly, safe, and efficient energy ecosystem to cope with emission reduction pressure and achieve internationally-aligned goals.

5 Analysis and Recommendations on China's Energy Transformation Enlightenment

5.1 Accelerate the optimization and upgrading of industrial structure

The key to achieving carbon peak and carbon neutrality lies in optimizing and upgrading the industrial structure. Firstly, efforts should be made to promote energy-saving and emission reduction and the green and low-carbon transformation of traditional industries, formulate related action plans, and build a sustainable and green industrial system. Secondly, clean energy utilization and the substitution of renewable energy should be promoted, energy efficiency should be improved, and total energy consumption should be reduced. The optimization and upgrading of the industrial structure should continue to promote the transformation of modern economic growth. R&D and industrialization of new energy vehicles and their components should be strengthened, and the construction of charging facilities for electric vehicles should be continued to promote the widespread application of new energy vehicles. The transformation of various industries using the new generation of information technology and green manufacturing technology should be accelerated, and the upgrading of the industrial chain promoted. Furthermore, strategic emerging industries should be actively developed to enhance the modernization levels of the industrial and application chains. Energy conservation, circular economy, and new energy technology development and application should be widely promoted, with increased focus on developing electric and hybrid vehicles and promoting the electrification, intelligence, and networking of vehicles to facilitate the development of

the new energy vehicle industry[22]. Finally, fiscal policies should be improved, and support for new energy enterprises increased to promote the sustained development of the new energy industry.

5.2 Building a clean and low-carbon energy system

The energy sector plays a crucial role in reducing carbon emissions and achieving decarbonization. China needs to accelerate the process of coal reduction, achieve energy-saving and emission reduction goals through adjusting industrial structure and optimizing energy structure. Accelerating energy conservation and emission reduction work, reducing energy consumption intensity, and controlling carbon dioxide emissions. Curtailing the expansion of high-energy-consuming and high-emission projects and ensuring the smooth progress of industrial projects. Promoting the development of circular economy, improving energy utilization efficiency, constructing green and low-carbon industrial, building and transportation systems, focusing on promoting industrial energy conservation work. Actively promoting renewable energy, expanding wind power generation scale, and developing other renewable energy. Promoting the application of solar energy, building photovoltaic power stations, and promoting clean energy technologies. Promoting the development of biomass energy, developing hydropower resources, establishing a reasonable electricity price mechanism and market trading system. Building a new type of power system, enhancing the capacity for accommodating and regulating renewable energy consumption. Implementing the energy audit system, promoting energy-saving lamps and supporting micro-grid project demonstrations. By taking these measures, China can achieve its energy sector emission reduction and decarbonization goals, and promote sustainable development.

5.3 Strengthening the development of CCUS technology

In the future, achieving carbon neutrality does not necessarily require complete reliance on non-fossil energy sources, and maintaining the use of fossil fuels in industrial processes may be the most cost-effective option. To ensure stable and reliable energy supply for economic development, it is necessary to manage and utilize fossil fuels reasonably and effectively. Carbon capture, utilization, and storage (CCUS) is an efficient method for carbon neutrality. Implementing CCUS technology in the remaining stages of fossil fuel use is one of the most effective carbon neutrality paths[23-24]. China has already begun exploring CCUS and has built some medium-scale demonstration equipment, but the related technology is not yet fully mature. There are still knowledge gaps in technical standards, implementation specifications, economic incentives, and management systems[25-27]. Therefore, it is recommended to strengthen policy support for the development, demonstration, and promotion of CCUS technology based on a reasonable proportion of fossil fuels. This will promote the rapid development of CCUS technology, providing sufficient technological reserves to achieve expected goals.

5.4 Leveraging the Positive Role of Market Mechanisms

To enhance the completeness of the carbon trading market, it is necessary to improve the transparency and information disclosure mechanisms for carbon emission quotas. Accelerate the establishment of binding carbon pricing mechanisms to promote the development of the carbon trading market. Improve the legal system of the carbon trading market and increase the influence of China in the global carbon market. At the same time, it is necessary to actively connect with the international carbon emission trading market to seek cooperation and development opportunities. Draw upon advanced foreign experience and promote the construction of the carbon trading market to achieve integration with international standards. Pilot diversified trading products and methods, and formulate corresponding regulatory norms. Conduct research on establishing a carbon rights market to support economic transformation. Develop accounting standards for carbon assets and carbon trading, ensuring accurate and transparent financial statements. Research the initial allocation system for carbon emissions rights. Establish low-carbon product standards, identification, and certification mechanisms, and formulate low-carbon certification standards, technology models, processes, and regulatory measures. By taking these measures, it is possible to improve the carbon trading market, promote the development of carbon finance, and provide funding support for economic transformation.

6 Conclusions

In summary, by optimizing the industrial structure, building a clean and low-carbon energy system, strengthening the development of CCUS technology, and leveraging the role of market mechanisms, we can promote the smooth progress of China's energy transformation, achieve carbon emission reduction goals, and promote sustainable development. These measures will provide important support and driving force for economic transformation.

Acknowledgments

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