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LOW-CARBON TRANSFORMATION OF CHINA'S COAL-FIRED POWER INDUSTRY: CURRENT SITUATION INSIGHTS AND TREND PROSPECTS

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Abstract: Considering the importance of global climate change mitigation, this paper focuses on the low-carbon transformation of China's coal-fired power industry. China's coal-fired power industry is large-scale. The geographical distribution of power plants is uneven, and the technical level shows an unbalanced pattern. The existing units are mainly those with capacities of 300-600MW and 600-1000MW, while most of the newly added units are advanced ones with high parameters. Although the proportion of coal-fired power installed capacity has decreased to 36.9% due to new energy, it still plays a crucial role in power supply. Clean coal technologies, such as ultra-supercritical units, have developed well, and technologies like green ammonia co-firing and CCUS have also made good progress. Coal-fired power is of vital importance in ensuring power security, system regulation, centralized heating, and reducing energy consumption costs. In terms of policies, the "1+N" system and local policies promote the low-carbon transformation.
Keywords: Coal-fired power; Power industry; China; Low-carbon transformation

1 INTRODUCTION

With the global high-level attention to climate change issues, the control of greenhouse gas emissions has become a consensus in the international community. As one of the world's largest energy consumers and carbon emitters, China shoulders significant responsibilities in addressing climate change. In the past few decades, China's economy has developed rapidly, and the energy demand has been continuously growing. Coal, as one of China's major energy sources [1], plays an important role in power . However, the traditional coal-fired power methods have problems such as low energy utilization efficiency and high carbon emissions, which run counter to the requirements of China's carbon neutrality goal [2].

Therefore, the low-carbon transformation of the coal-fired power industry is of utmost significance for China's sustainable energy development [3]. Achieving a low-carbon transformation can effectively reduce coal consumption and carbon dioxide (CO2) emissions, mitigate the negative impact on the environment, and propel China's transition towards a green and low-carbon economy. Through technological innovation and industrial upgrading, the energy utilization efficiency of coal-fired power can be improved, power costs can be reduced, and the competitiveness of China's energy industry can be enhanced [4]. The low-carbon transformation of the coal-fired power industry can also drive the development of related industries, such as new energy, energy conservation, and environmental protection, injecting new impetus into economic growth.

The development status and trends of the low-carbon transformation of China's coal-fired power industry has important practical significance for formulating scientific and reasonable policies and measures, promoting the sustainable development of the coal-fired power industry, and achieving China's emission control goals [5]. Research on the low-carbon transformation of the coal-fired power industry can provide a basis for decision-making for China's departments, guiding them to formulate more effective policies to promote energy structure adjustment and energy conservation and emission reduction. For coal-fired power enterprises, understanding the trends and paths of low-carbon transformation can help enterprises make early arrangements, increase investment in technological research and development, and improve their own competitiveness. Research in this field can also provide references for the academic community, promoting the development and improvement of relevant theories.

2 THE CURRENT STATUS OF CHINA'S COAL-FIRED POWER INDUSTRY

2.1 Geographical Distribution of Power Plants

The current situations of coal-fired power units vary in different regions of China. In the Northeast region, units with a capacity of 300,000 kilowatts and above are dominant. Some of them need energy-saving and flexibility retrofits to adapt to the consumption of new energy and peak-shaving of the power grid. The North China region, being a major coal-producing province, has a huge installed capacity of coal-fired power. The proportion of cogeneration units exceeds 50%. However, there are many small and medium-sized units, which need to be upgraded, retrofitted, and backward production capacity phased out. Also, due to its proximity to Beijing and Tianjin, strict environmental protection requirements are in place. In the East China region, the scale of coal-fired power ranks first in the country. There are many self-supplied power plants, and the proportion of large-scale units is relatively high, but some small-

scale units need to be phased out or retrofitted. Some units have already undergone flexibility retrofits to meet the demand for new energy integration. In the Central China region, large-scale units with a capacity of 600,000 kilowatts and above are dominant. The region is actively promoting retrofit and upgrade and strengthening power grid interconnection. In the Northwest region, the installed capacity of coal-fired power is large and diverse in types. It is necessary to accelerate flexibility retrofits to ensure the power grid operation and new energy consumption. In the future, flexibility retrofits are needed to promote energy transformation. In the South region, the 1-million-kilowatt ultra-supercritical units along the coast of Guangdong Province are dominant. The region is promoting multi-energy complementarity to improve comprehensive utilization efficiency. In other provinces, clean energy will be the main focus in the future. Generally speaking, the distribution of coal-fired power plants in China is shown in Figure 1 and has the following characteristics.

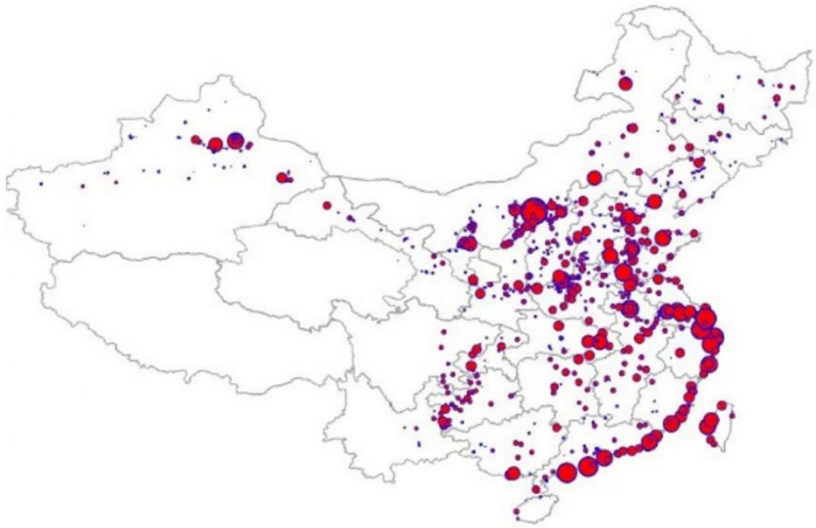

Figure 1 Distributions of all China's Coal-Fired Power Plants, with Capacity Sizes

First, the geographical distribution is unbalanced. The distribution of coal-fired power is significantly influenced by the distribution of coal resources. Coal-fired power is mainly concentrated in regions with abundant coal reserves. For instance, in China, Shanxi, Inner Mongolia, and Shaanxi are major coal-producing provinces. Besides resource-rich areas, coal-fired power also has a certain distribution in regions with developed economies and high electricity demand. Take the eastern coastal areas of China as an example. Although they are relatively scarce in coal resources, due to their developed industries and dense population, the demand for electricity is huge.

Secondly, the focus is close to the consumption centers, but there is still a need for power transmission from the west to the east. Some coal-fired power enterprises are located near energy consumption centers, which helps to reduce power losses during transmission. Excessively long power transmission distances will lead to increased power losses. Building coal-fired power facilities near consumption centers can effectively reduce such losses and improve energy utilization efficiency. However, coal-fired power in China is also supplied across regions. There is a mismatch between the coal-producing areas and the energy consumption centers. It is necessary to build high-voltage transmission lines to transport coal-fired power from the producing areas to regions with high demand. China's "West-to-East Power Transmission" project includes a large amount of coal-fired power transmission, transporting electricity from coal-rich areas in the west to the economically developed eastern regions.

Furthermore, the technical level shows a pattern of "higher in the south and lower in the north". In regions with a higher technical level and stronger economic strength, coal-fired power enterprises tend to adopt more advanced power-technologies. For example, ultra-supercritical coal-fired power-technology is mainly concentrated in some coastal areas with developed economies and high requirements for environmental protection and energy efficiency. In some relatively underdeveloped regions, traditional and less efficient coal-fired power technologies still dominate. These regions may find it difficult to quickly update their power-technologies due to limited funds and difficulties in technology introduction. This difference in technical level has led to uneven development quality and environmental protection levels of the coal-fired power industry in different regions, and also affects the overall pattern of coal-fired power distribution.

2.2 The Technical Levels of Current Power Units

Based on the cross-comparison between China's Coal-fired Power Unit-level Database and IEA statistical data [6-7], the capacity levels of existing coal-fired generator sets and incremental projects in China are shown in Figure 2. The existing capacity is approximately 1.109 billion kilowatts. There are still 94 million kilowatts and 202 million kilowatts of coal-fired power projects under construction and awaiting construction respectively. In particular, the planning and construction of ultra-high-voltage power grids have become one of the key projects of the "new infrastructure".

Regarding the structure of coal-fired power installed capacity, among the existing units nationwide, the two types of units with capacities of 300-600MW and 600-1000MW are dominant. The units under construction and awaiting construction are mainly large-scale units with higher parameters. The proportion of units with capacities of 600-1000MW and above 1000MW is much higher than that of other types. With the construction and commissioning of advanced incremental units and the improvement of the quality and efficiency of existing units, the power-efficiency of coal-fired power will be further enhanced.

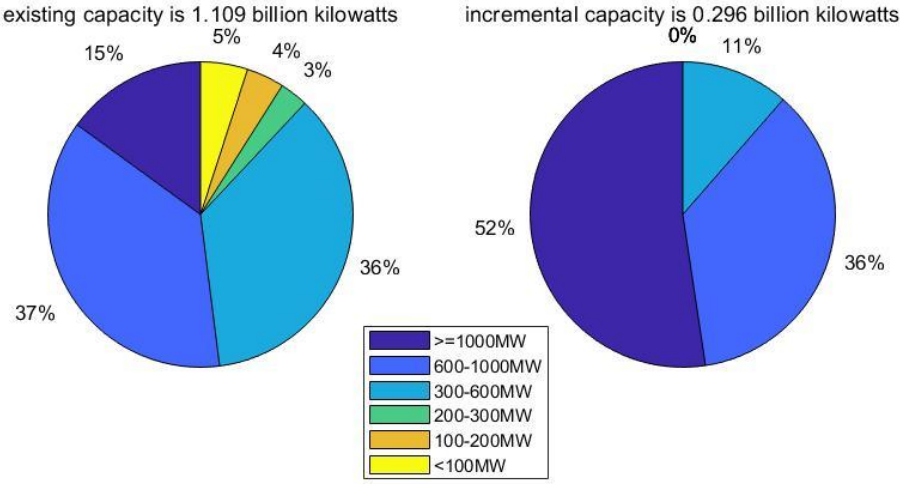

Figure 2 The Composition of China's Existing and Incremental Coal-Fired Power Units

In recent years, through measures such as "building large-scale units while phasing out small-scale ones", "equivalent replacement", and eliminating backward units, the energy efficiency of China's existing coal-fired power units has been effectively improved. The coal consumption per kilowatt-hour is approximately 305 grams of coal equivalent (gce/kWh), which is already better than that of developed economies such as the United States and Germany. At the same time, a large number of newly added coal-fired power projects are high-parameter coal-fired power units of 1000MW and above. The coal consumption per kilowatt-hour of units under construction and to be constructed is even as low as 276 gce/kWh. Therefore, the relatively short service life of China's coal-fired power units means that large-scale elimination in the short term is less feasible, and improper transformation may lead to higher risks.

With the rapid development of China, the electricity consumption of the whole society has been continuously increasing, putting forward higher requirements for power supply. To ensure the leapfrog development of China's power industry and provide affordable and stable electricity for the country's economic and social development, coal-fired power plays a crucial role. As shown in Figure 3, from 2009 to 2023, the installed capacity of coal-fired power continued to rise. However, with the increase in the installed capacity of new energy power , the proportion of coal-fired power installed capacity has dropped to 36.9%, a decrease of 23.4% over ten years.

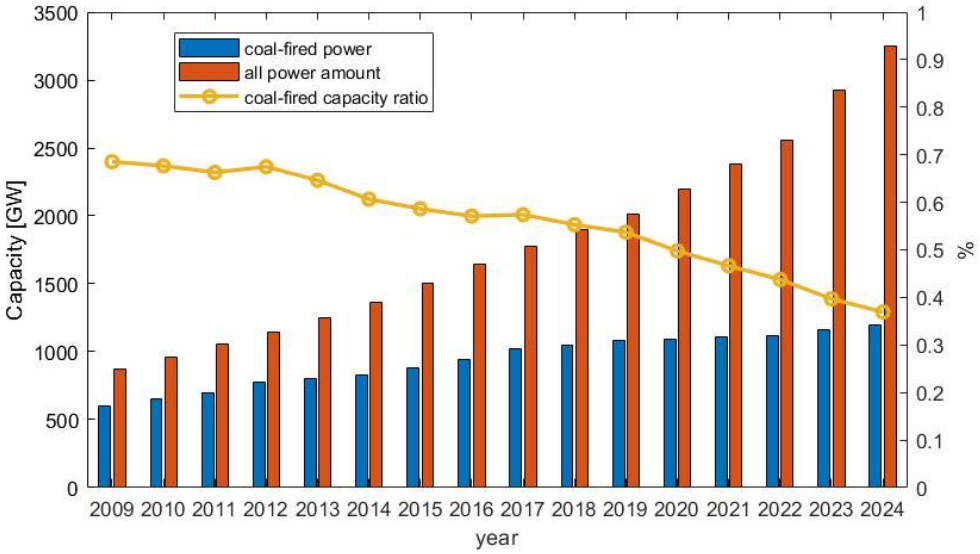

Figure 3 The Installed Capacity, Proportion and Growth Rate of Coal-Fired Power in China from 2009 to 2024

In terms of power amount, driven by the rapid growth of the installed capacity of new energy power , although China's coal-fired power reached 5.38 trillion kWh in 2023, accounting for 53.6% of the total power , this proportion has

decreased by 16.2 percentage points over the past decade. This reflects the rapid growth of new energy power and the gradual optimization of the energy structure. Nevertheless, coal-fired power plays an irreplaceable role in ensuring national energy security and the stable operation of the economy. With the advancement of clean energy technologies and the promotion of policies, coal-fired power and new energy will form a more coordinated development pattern.

2.3 Low-carbon Technology Level and Development Trends

Among relevant low-carbon technologies, clean coal technology refers to the general term for new technologies in the whole process of coal development and utilization, including processing, combustion, conversion, and pollution control technologies that reduce pollutant emissions and improve utilization efficiency. It mainly includes two aspects: one is the clean technology for direct coal combustion, and the other is the technology for converting coal into clean fuels. Regarding coal-fired power , clean coal power technologies mainly refer to power-technologies with obvious emission-reduction effects, such as ultra-supercritical units, integrated gasification combined cycle (IGCC) power , green ammonia co-firing, carbon capture, utilization and storage (CCUS). Clean coal technology is one of the leading technologies in the world to solve environmental problems, and efficient and clean coal-fired power is the main focus of clean coal technologies in various countries.

Since 2007, the National Development and Reform Commission has required that all newly built coal-fired units must be supercritical and ultra-supercritical units. These two types of units have entered a fully commercial stage in China. Vigorously developing large-capacity, high-parameter supercritical and ultra-supercritical units can significantly reduce coal consumption, save coal resources, reduce carbon dioxide emissions, and lower the emission level per unit of electricity. Since 1978, with the progress and development of technology, China's standard coal consumption for power supply has been decreasing year by year, from 471 grams/kWh to the current 305 gce/kWh, and the gap with the coal consumption for power in developed countries is gradually narrowing.

In recent years, by digesting and absorbing advanced foreign IGCC technologies, China has improved its local design, manufacturing capabilities, and R & D levels, promoted the localization of gas turbines, with the localization rate reaching 85%. According to the IGCC projects under construction in China, the construction cost is 7,000-8,000 yuan/kW. With the maturity of technology, equipment optimization, especially the full-scale promotion of localization, IGCC is rapidly developing towards high-efficiency, low-carbon, large-scale, and commercialization.

Overall, clean coal power technology has good technical and economic characteristics, which is conducive to improving power-efficiency, saving resources, and reducing pollutant and carbon dioxide emissions. Vigorously developing clean coal power is an effective measure to optimize and upgrade coal-fired power technology, and it is also the main direction of low-carbon development of China's coal-fired power .

The carbon-reduction principle of the green ammonia co-firing technology is based on the green preparation process and clean combustion characteristics of green ammonia. In terms of application cases, the National Energy Group carried out a coal-ammonia co-firing combustion test under high-load power-conditions at the Taishan Power Plant in Guangdong. This is currently the largest-capacity unit that has completed the ammonia-co-firing combustion test verification at home and abroad. This test has provided valuable practical experience for the large-scale application of green ammonia in the coal-fired power field, and promoted the green ammonia co-firing technology towards commercial application.

CCUS technology refers to the process of separating carbon dioxide from industrial or related energy sources, transporting it to a storage site, and keeping it isolated from the atmosphere for a long time. The CCUS technology has a significant effect on greenhouse gas emission reduction. Research [8] shows that the contribution rate of CCUS to carbon dioxide emission reduction is expected to be more than 50% in the future. The first CCUS demonstration project jointly built by China and Australia, with an annual recovery capacity of 3,000 tons, the Huaneng Beijing Thermal Power Plant, has started operation. China Datang Corporation and Alstom jointly cooperate to develop two CCUS demonstration projects with an annual carbon dioxide capture capacity of over 1 million tons in Daqing, Heilongjiang, and Dongying, Shandong. The China Power Investment Corporation independently developed and fully adopted domestic equipment to build an annual 10,000-ton liquid carbon dioxide capture device at the Shuanghuai Power Plant in Chongqing, marking the development and breakthrough of domestic carbon dioxide capture technology in China, and laying a good foundation for China to achieve clean coal power and the low-carbon development of the coal-fired power industry.

3 DEVELOPMENT TRENDS OF CHINA'S COAL-FIRED POWER INDUSTRY

3.1 Ensuring Power Security

New energy power is characterized by randomness, volatility, and intermittency, with a low effective capacity, making it difficult to guarantee real-time electricity demand. The peak power load of the power grid generally occurs between 18:00-20:00. During this period, the power output of photovoltaic power is basically zero, and the power output of wind power is less than 10% of the installed capacity. If extreme weather conditions are added, such as continuous days of low wind or rainy and cloudy days, secondary disasters affecting energy security are likely to occur, triggering a chain reaction in the power system. For example, in early 2021, Texas in the United States was hit by rain, snow, and freezing natural disasters. While the electricity load surged, the harsh weather caused pipeline ice blockages, gas source interruptions, and icing of wind power equipment. Gas-fired and wind-power units successively shut down, leading to a

major power outage. The production and lives of nearly 4 million people were severely affected, causing immeasurable economic losses. Since China has insufficient flexible resources such as gas-fired units, and the energy storage system is in the initial development stage and is still difficult to play a significant role in power regulation, coal-fired power remains an important power source to support the stable and reliable operation of the power system under major accidents and extreme disasters, ensuring power supply security.

3.2 Providing System Regulation

With the accelerated development of new energy, the system's demand for flexible power sources will continue to increase. In China, most hydropower stations are run-of-river type. The regulation capacity is limited due to the lag in the construction of regulating and key hydropower stations. Pumped-storage power stations are restricted by site resources, and gas-fired power stations are limited by gas sources and gas prices, making large-scale construction unfeasible. Nuclear power is restricted by safety and economic factors and is not suitable for frequent regulation. Energy storage is affected by technical maturity and economy and does not yet have a competitive advantage. Coal-fired power units operate stably and reliably. After transformation, they can change their load over a wide range. Under the current technical conditions and energy resource endowment, coal-fired power is the most economical and reliable large-scale flexible regulating power source. The flexibility transformation of coal-fired power is a practical choice to improve the system's regulation capacity.

3.3 Undertaking Centralized Heating

For a long time, the power industry has been the main force in clean heating. Since the 1990s, combined heat and power (CHP) units have replaced highly polluting heating boilers, playing a huge role in solving heating problems in northern China and improving the environment. In China, hundreds of millions of tons of coal are burned for heating in a decentralized manner. At the present stage, it is difficult to completely replace them with gas or electricity. The most effective way is to replace them with CHP. Currently, the proportion of coal used for power and CHP heating in China accounts for 50% of total coal consumption. About half of the coal-fired power units are CHP units, and the proportion of heating units in the "Three North" regions is as high as 60%. Centralized heating by coal-fired power replacing scattered coal burning and undertaking clean heating in northern China in winter is an important measure to ensure people's livelihood under the premise of environmental friendliness.

3.4 Reducing Energy Consumption Costs

As new energy is a power source with low energy density, to meet electricity demand, it is necessary to significantly increase the installed capacity. In 2023, China added 290 million kW of new energy, reaching a record high of 89.2% [9]. Since the "14th Five-Year Plan" period, the average annual investment in power sources has reached 767 billion yuan [10], and the annual investment in power source projects has reached 967.5 billion yuan, of which non-fossil energy accounts for more than double the previous annual investment in power sources of 350-380 billion yuan. With technological progress, the cost of wind and solar power will decrease, but in the short term, it is still difficult to offset the increase in electricity costs caused by the rise in system costs due to changes in the power system structure. As the main supplier of electricity and heat, coal-fired power is an important guarantee for the whole society to use electricity and heat fairly at present and in the future.

4 POLICIES RELATED TO THE LOW-CARBON TRANSFORMATION OF COAL-FIRED POWER

It is extremely difficult for China's coal-fired power to withdraw in the short term. Its future development and the gradual withdrawal path are crucial for China to achieve the carbon peak and carbon neutrality goals. In 2021, the central supervision department established a working group for carbon peak and carbon neutrality, and began to construct a "1 + N" policy system. Here, "1" refers to one top-level design document, and "N" refers to a series of policy plans for key action areas. Due to China's coal-dominated energy structure, coal-fired power occupies the position of the main power source in the entire power system. However, recognizing the pollution and high-emission problems of coal-fired power plants, given the high-emission and high-pollution characteristics of coal-fired power, the Chinese supervision department formulated a series of measures related to mitigating the emissions of coal-fired power plants during the past four Five-Year Plan periods from 2001 to 2020, and achieved specific results.

First, regarding the high-pollution problem, for example, in 2007, in order to accelerate the elimination of obsolete coal-fired technologies, the National Development and Reform Commission put forward the "Opinions on Accelerating the Shutdown of Small Thermal Power Units". It required the closure of small and obsolete units, and gave priority to the development of efficient and large-scale coal-fired power plant units. This policy has been particularly successful in reducing various air pollutant emissions, especially carbon dioxide emissions, and has made a significant contribution to reducing the emissions of China's coal-fired power plants. In addition, to reduce the use of raw coal, the advocated coal-to-gas project plays a crucial role in reducing the inventory carbon emissions of coal-fired power plants. The implementation of this policy is expected to reduce emissions by 280-300 million tons by 2030. The supervision department has also formulated a series of other plans and documents to address the issue of improving the energy efficiency of coal-fired power plants and dealing with emission reduction problems. In 2014, the "Opinions on

Promoting the Clean and Efficient Utilization of Coal" was introduced, and in 2015, the "Implementation Plan for Ultra -low Emission and Energy-saving Reconstruction of Coal-fired Power Plants" was formulated. In addition, during the 13th Five-Year Plan period, significant progress was made in the implementation of the five-year power development plan. In 2020, China's coal-fired power installed capacity was less than 50% of the total national installed capacity for the first time, and the carbon emission factor in most provinces decreased by 3%-6%.

Carbon emission reduction of coal-fired power plants remains an important issue. Therefore, the Chinese supervision department has formulated the latest national 14th Five-Year Plan. At the beginning of the 14th Five-Year Plan, the supervision department issued the guiding "14th Five-Year Plan for the Modern Energy System" and the "Implementation Plan for the Transformation and Upgrading of National Coal-fired Power Units". These policies put forward specific clean-energy requirements for coal-fired power plants at the national level, and will guide the development, transformation, and decommissioning of all coal-fired power plant units until 2025. Subsequently, various provinces across the country have successively introduced relevant policies for energy conservation, emission reduction, and clean-up transformation of coal-fired power. For example, in July 2023, Henan Province introduced the "Three-year Action Plan for Promoting the Stable Improvement of the Ecological Environment Quality in Henan Province (2023-2025)". In August 2023, Shandong Province issued the "Action Plan for the Transformation and Upgrading of the Coal-fired Power Industry in the Province".

5 CONCLUSION

This paper elaborates in detail on the current situation of China's coal-fired power industry and the development of key energy-saving and emission-reduction technologies in the low-carbon transformation of coal-fired power. In the analysis of the current situation of the coal-fired power industry, first, based on regions, the distribution characteristics, installed capacity of coal-fired power units, and power of coal-fired power plants in China are summarized. Secondly, an analysis is conducted on the currently popular low-carbon technologies for coal-fired power, describing the current situation and development trends of these key energy-saving and emission-reduction technologies from multiple aspects. Then, the relevant policies for the low-carbon development of coal-fired power are sorted out, which can provide support for subsequent research. Overall, the low-carbon transformation and development of China's coal-fired power industry is showing a stable and positive trend, but there are still many difficulties that need to be overcome.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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