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RESEARCH

Prospects for the transformation and development of carbon storage in abandoned mines of coal enterprises from the perspective of carbon neutrality

Xin Lyu[1] · Tong Zhang[1,2] · Liang Yuan[1] · Juejing Fang[1]

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Abstract
Under the carbon neutrality goal, coal enterprises must seek breakthroughs from abandoned mines, develop new resources in the new era, turn problems into countermeasures, and participate in the carbon emissions market, for contributing to the accomplishment of the national strategic goal of carbon neutrality. To this end, we investigated the relevant national policies and regulations to clarify the boundaries disclosed by the carbon information of enterprises, understood the development direction of carbon storage in abandoned mines, and clarified the transformation and development of carbon storage in abandoned mines. We made a few suggestions: (1) China should learn from its past experience and other countries to develop the energy industry with Chinese characteristics and reform the economic system. (2) Coal enterprises must actively respond to the national carbon information disclosure policy, clarify their own responsibilities and carbon emission boundaries. (3) It is necessary to proactively obtain advanced knowledge and plan carbon storage pathways for abandoned mines. (4) Development problems of coal enterprises should be deduced using cases. The 'dual carbon' goals should be achieved steadily step-by-step. (5) Three measures, i.e. improving the existing resource structure, coordinating the information of abandoned mines, and promoting the cultivation of scientific and technological talents.

Keywords Mining engineering · Abandoned mines · Carbon neutrality · Carbon emission rights · Carbon tax

1 Introduction

The Chinese government has made a solemn commitment to the international community to achieve carbon peaking and carbon neutrality (Fig. 1). China officially raised the carbon emission peaking and carbon neutrality goals (hereinafter referred to as 'dual carbon' goals) to the national strategic level and began to develop a carbon neutrality layout in the 14th Five-Year Plan.

From the perspective of the central government, the State Council of China issued the *Guiding Opinions on Accelerating the Establishment and Improvement of a Green and Low-Carbon Circular Economic Development System*, requiring China 'to establish and improve a green and low-carbon circular economic development system, so as to achieve 'dual carbon' goals and drive China's green development to a new level' (Wang et al. 2021). Additionally, the *Outline of the 14th Five-Year Plan for National Economic and Social Development and Vision 2035 of the People's Republic of China* suggests that China should 'prioritise and pursue the policy of energy conservation; strengthen energy-saving management of key energy users; implement energy system optimisation and energy-saving technology transformation and other key projects; and accelerate the formulation and revision of mandatory national standards for energy consumption quota and energy efficiency of products and equipment' (Huang et al. 2021).

From the perspective of local governments, 31 provinces, municipalities, and autonomous regions have publicly formulated development plans and energy structures for the 'dual carbon' goals in their government work reports. Many localities have formed pilot systems and started low-carbon projects. According to incomplete statistics, the construction

✉ Xin Lyu
xin_lyu2020@163.com

1 State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Anhui University of Science and Technology, Huainan 232001, China

2 Institute of Energy, Hefei Comprehensive National Science Center, Hefei, 230031, China

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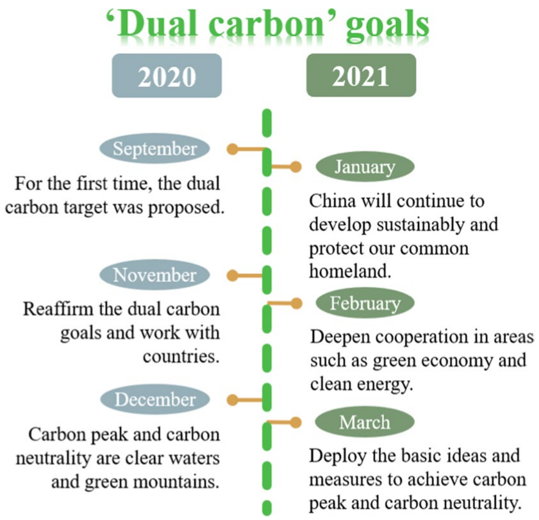

Fig. 1 Carbon peaking and carbon neutrality goals

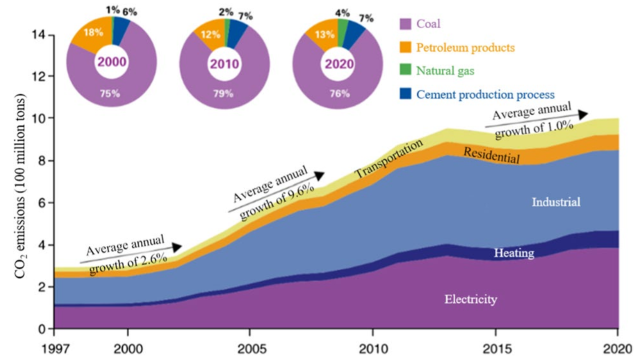

Fig. 2 Carbon emission data over the years (data source: Annual Report on China's Carbon Neutrality and Clean Air Synergy Pathway (2021))

of six low-carbon provinces (autonomous regions), 81 low-carbon cities, 52 low-carbon industrial parks, more than 400 low-carbon communities, and eight low-carbon villages and towns has started. Additionally, a national carbon emission trading platform has been formed in nine regions (including Beijing, Shanghai, Tianjin, and Chongqing) (Chen et al. 2021).

From the perspective of industries and enterprises, despite the challenges introduced by the adjustment of the energy structure, the considerable opportunities of market transformation have given rise to new industries and business models. Enterprises such as State Grid, Ali Group, and CITIC Group have released action white papers and internal review systems. Some enterprises have seized the opportunity. For example, TCL Co., Ltd. established a carbon and new energy management subsidiary; Guilin Bank has realised the pledging of the right of expected earnings in terms of the carbon sink of tea gardens; and Zhengzhou Yuzhong Energy Sources Co., Ltd. entered the carbon trading market with a profit of more than CNY 30 million (Guo 2021).

In China, coal consumption has long occupied a large proportion of the energy consumption (Li 2021a, b; Mohr et al. 2021). With the continuous increase in total energy consumption, the total amount of carbon dioxide (CO_2) emitted by coal combustion has more than doubled in the past 20 years (Fig. 2). The adjustment of the energy structure and control of coal consumption will inevitably affect the source enterprises of coal mining (Chen et al. 2021). Therefore, coal enterprises must clarify their social responsibility for carbon emission reduction and fully understand national policies and regulations, establish the carbon footprint relationship between upstream and downstream enterprises in the coal lifecycle, strictly examine their own carbon emissions, promote research and development of emerging technologies, adjust the internal structure of the industry, change the direction of project investment, use carbon storage of abandoned mines to achieve corporate transformation and profiting, seize the carbon trading market, and fulfil the social value of enterprises and the strategic goal of carbon neutrality. This article is based on existing international carbon neutrality policies, and studies and judges the future form of carbon neutrality in China. Clarify the carbon emission boundary and accounting method of coal enterprises. According to the environment of the abandoned mine, the transformation development path is proposed. The specific data is calculated by the scenario analysis method. Finally, comprehensive recommendations are presented.

2 Carbon neutrality policies in China and abroad

With the rapid development of the national economy and social productivity, the most significant problem facing China is balancing the development rate and environmental ecology. The focus of the debate is how to protect the environment while taking into account the development of the economy for achieving the 'dual carbon' goals as soon as possible. Carbon neutrality suggests not only the gradual restriction of the consumption of traditional fossil energy in the energy market but also the transformation of the entire economic structure and production technology. Carbon neutrality also implies the transformation of China's economic model and changes in the national lifestyle in the future.

Since the 1980s, the Intergovernmental Panel on Climate Change (IPCC) has issued several assessment reports (Li et al. 2022) identifying the problems facing the global ecological environment, which has attracted extensive international attention. Multiple international negotiations have provided a political and legal basis for countries to address climate change. Among them, the United Nations

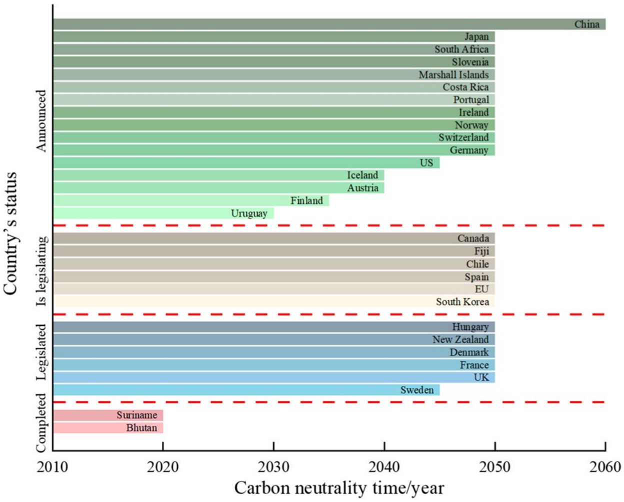

Fig. 3 Countries committed to carbon neutrality

Framework Convention on Climate Change has established the principle of common but differentiated responsibilities. Kyoto Protocol for the first time to limit greenhouse gas emissions in the form of regulations. The Paris Agreement limits the increase in global average temperature to well below 2 °C above pre-industrial levels. By the end of 2020, government departments in more than 40 countries and regions had announced the time for achieving carbon neutrality goals and issued many laws, regulations, and policy documents (Fig. 3).

Countries around the world have generally reached a consensus on carbon neutrality and environmental governance, but there are significant differences among governments with regard to carbon neutrality attitudes and policies.

Owing to changes in government dominance, the United States (US) often makes contradictory and repeated decisions (Guo 2012). The US became the first country to withdraw from the Paris Agreement under the Trump administration but re-joined the Paris Agreement and vigorously promoted the country's carbon reduction behaviours under the Biden administration. From the perspective of national measures, the US government attempts to realise the transformation of clean energy and public transportation and to promote the new energy industry by reducing the tax rate and extending the credit period (Table 1).

The European Union (EU) is a global industry leader and a region that pioneered the adjustment of the energy structure. Since 1990, the coal consumption of the EU has decreased. In the past 30 years, the coal supply has decreased by 55.15%, the natural gas supply has increased by 35.56%, the supply of renewable energy has increased by 308.01%, and nuclear energy has accounted for 14%. The EU announced that the proportion of renewable energy will reach approximately 40% in 2030. It has created a complementary development model among its member states with its unique community structure. Taking Germany as an example (Table 2), its standards are stricter than those of the EU as a whole (Yang et al. 2016), and the country reached the carbon emission peak prior to 1990. In less than 20 years, the coal consumption in Germany has decreased by 66.35%, and the wind and solar resources have increased by nearly 600% (Kost et al. 2021).

The climate policy of the Australian government is also vacillating because of the change of leaders. It was not

Table 1 Carbon emissions policies formulated by the US government

President	Term of office	Related policies	Carbon emission reduction (%)
George Walker Bush	2001–2009	The US refused to sign the Kyoto Protocol	6.4
Barack Hussein Obama	2009–2017	The US joined the Paris Agreement and proposed a Clean Power Plan	4.8
Donald Trump	2017–2020	The US became the first country to withdraw from the Paris Agreement	0
Joseph Biden	2021–Now	The US returned to the Paris Agreement and passed the Build Back Better Act	—

Table 2 Carbon neutrality policies of Germany

Formulation year	Related policy
2008	German Strategy for Adaptation to Climate Change
2011	Climate Protection Plan 2050 and Adaptation Action Plan
2017	Renewable Energy Act
2019	Climate Action Plan 2030, Federal Climate Protection Act, and Energy Efficiency Strategy 2050
2020	National Hydrogen Strategy

until 2007 that the Kyoto Protocol was signed. Repeal Australia's Energy Guarantee Plan climate policy since Scott Morrison became Prime Minister in August 2018. And the Climate Solution released on February 25, 2019, plans to invest 3.5 billion Australian dollars to fulfill Australia's 2030 greenhouse gas emission reduction commitment in the Paris Agreement. The new prime minister, Anthony Albanese, will legislate after taking office in 2022 to reduce carbon emissions by 43% by 2030 compared to 2005 levels and sign a global commitment (Udemba and Alola 2022).

As a highly developed country in Asia, Japan proposed in October 2020 the achievement of carbon neutrality by the middle of the century (Geng 2014). Japan released the Green Growth Strategy Through Achieving Carbon Neutrality in 2050, which set the goal of reducing carbon reduction by 50% by 2030. This strategy aims to guide the future development direction of 14 important industrial fields across Japan from multiple levels, such as government, finance, and education (Table 3).

African countries are actively promoting green energy transformation and greenhouse gas emission reduction actions, and promoting capacity building for sustainable development. The African Union's Agenda 2063 regards improving the ability to respond to climate change and achieve sustainable development as one of its important goals. Fifty-four countries have unanimously agreed to implement a green recovery plan, and more than 90% of African countries have formally ratified the Paris Agreement on climate change. More than 70% of African countries have included the development of clean energy and clean agriculture in their nationally determined contributions to combat climate change. The South African government continues to introduce measures to encourage the development and utilization of renewable energy, and proposes to reduce the proportion of coal power to 48% by 2030, and achieve carbon neutrality by 2050 (Adjei et al. 2022).

China has always been brave and dared to assume 'China's responsibility' on a global scale; it takes responsibility as a world power and plays an active part in contributing to the world's environment. In particular, China strives to reach the peak of CO_2 emissions by 2030 and achieve carbon neutrality by 2060.

To achieve the goal of carbon neutrality, China must develop a low-carbon and efficient economy. To realise carbon-negative carbon storage technology, China must abandon the past high-emission, high-pollution, and high-energy-consumption development projects and promote low-emission, highly efficient, and carbon-negative carbon storage industries instead (Shi 2021). China has established a prototype of the carbon neutrality policy system (Table 4) and has actively explored and guided pathways to achieve carbon neutrality in all industries. Additionally, China will make efforts in both low-carbon development and carbon absorption. The first task is to promote the development of renewable energy and the innovation of clean energy utilisation technology. Another goal is to control the amounts of environmental pollutants in industries with serious carbon emissions and reduce emissions from the source. It is also necessary to accelerate the construction of carbon storage and carbon utilisation projects, select demonstration sites across the country, and implement the concept of carbon emissions trading. In accordance with the national 'carbon neutrality' strategy, China must coordinate various ministries, local governments, and industries to form a pattern in which the central policies lead the development of local regulations and industry standards, to build a free trade business model for enterprises under the unified national carbon trading market.

3 Carbon information disclosure of coal enterprises

The concept of 'carbon information' was proposed by Iversen. As a type of non-financial data, carbon information can provide insight regarding the energy efficiencies and low-carbon management capabilities of enterprises and can

Table 3 Carbon neutrality policies of Japan

Policy level	Main content
Government funds	Establish a 2 trillion yen 'Green Innovation Fund' for the technological development of the new energy industry and induce private companies to invest 15 trillion yen
Tax incentives	Establish a carbon–neutral investment tax incentive system (tax deduction or depreciation) with a maximum tax deduction of 10%, which is expected to induce private investment of 1.7 trillion yen
Financial system	Formulate the financial guidelines for the transition to carbon neutrality and establish a long-term funding mechanism and a results-linked interest subsidy system
Regulatory mechanism	Formulate industry standards for carbon emission reduction and a regulatory system for the carbon trading market, carbon tax, and carbon border
Education system	Develop an education and research system that contributes to carbon neutrality and promote cross-disciplinary research to achieve carbon neutrality

Table 4 Carbon neutrality policies of China

Leading department	Formulation time	Policy	Content
National Development and Reform Commission	March 2009	Guiding Catalogue for Green Industries (2019 Edition)	Limited policies and funds are directed toward the most critical industries for promoting green development, including the energy conservation and environmental protection industry, clean production industry, clean energy industry, ecological environment industry, green infrastructure upgrade, and green services (Zheng 2020)
National Development and Reform Commission	November 2009	Guiding Catalogue for Industrial Restructuring (2019 Edition)	The catalogue is divided into three categories: encouraged (60 items added), restricted (8 items decreased), and eliminated (17 items added). China should take supply-side structural reform as the main task, the development of a modern industrial system as the goal, and the high-quality development of the manufacturing industry as the focus (Fan et al. 2020)
State Council	March 2020	Guiding Opinions on Building a Modern Environmental Governance System	By 2025, an environmental governance system with a clear orientation, scientific decision making, strong execution, effective incentives, multi-party participation, and benign interaction will be formed (Wu et al. 2021)
Ministry of Transport	July 2020	Plan for Creating Green Commuting Actions	For cities attempting to create green commuting actions, the proportion of green commuting should reach 70%, and the satisfaction rate of green commuting services should be greater than 80%
Ministry of Ecology and Environment	December 2020	Measures for the Administration of Carbon Emissions Trading (for Trial Implementation)	China should give full play to the role of the market mechanism in addressing climate change and promoting green and low-carbon development, further strengthen the control and management of greenhouse gas (GHG) emissions, promote the reduction of GHG emissions, and standardise carbon emission trading and related activities across the country
Ministry of Ecology and Environment	January 2021	Guiding Opinions on Coordinating and Strengthening Work Related to Addressing Climate Change and Ecological Environmental Protection	By 2030, the overall joint efforts of addressing climate change and ecological environmental protection will be brought into full play, and the ecological environment governance system and governance capacity will be steadily improved, providing support for the goal of peaking CO_2 emissions and the vision of carbon neutrality and helping build a beautiful China (Jiang et al. 2022)

Table 4 (continued)

Leading department	Formulation time	Policy	Content
State Council	February 2021	Guiding Opinions on Accelerating the Establishment and Improvement of a Green, Low-Carbon, and Circular Economic System	By 2025, the industrial structure, energy structure, and transportation structure will be apparently optimised; the proportion of green industries will be significantly increased; the total amount of major pollutant emissions will be reduced; the carbon emission intensity will be significantly reduced; the ecological environment will be improved; the market-oriented green technology innovation system will be more complete; the laws, regulations, and policy systems will be more effective; and the green, low-carbon, and circular industrial system and consumption system will take shape (Zhang and Huang 2022)
Ministry of Ecology and Environment	March 2021	Notice on Strengthening the Work Related to Corporate Greenhouse Gas Emissions Control	The norms for reporting GHG emissions and the emission allowances for specific industries and enterprises are clarified
State Council	October 2021	Opinions on Completely and Accurately Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutralisation	Efforts to proactively take the lead in peaking carbon emissions, save energy resources, give play to the role of market mechanisms, and reduce carbon safely are encouraged. The goal of these efforts is to ensure national energy security and economic development (Ren et al. 2022)
Sichuan Province	January 2021	2021 Government Work Report	Sichuan Province should set up a forest chief scheme and complete afforestation of 5.5 million mu to improve the carbon sink capacity of the ecosystem
Guangdong Province	January 2021	2021 Government Work Report	Guangdong Province should cultivate and expand the energy-saving and environmental protection industry, promote the application of energy-saving, low-carbon, and environmental protection products, and fully implement green buildings
Shanghai	June 2021	Shanghai's 2023 Key Work Arrangements for Energy Conservation, Emission Reduction, and Climate Change	Shanghai should resolutely curb the blind development of high-energy-consumption and high-emission projects and strictly implement the energy-saving review system and environmental impact assessment system for fixed asset investment projects in accordance with the law
Shanxi Province	January 2021	2021 Government Work Report	Shanxi Province should explore the adoption of energy use rights and the development of carbon emission trading markets
People's Bank of China	April 2021	Catalogue of Green Bond Endorsed Projects (2021 Edition)	The standards and uses of green bonds are unified, and the classification is refined. In particular, industries such as green equipment manufacturing and green services are added, and high-carbon emission projects such as clean utilisation of fossil energy (e.g. coal) are excluded (Xin and Tang 2021)

Table 4 (continued)

Leading department	Formulation time	Policy	Content
People's Bank of China	May 2021	Green Finance Evaluation Scheme for Financial Institutions in the Banking Industry	Green bonds are incorporated into the evaluation system, and green finance evaluation results are included in the policies and prudential management tools of the People's Bank of China, such as the central bank's financial institution rating (Xian and Chu 2022)
China Southern Power Grid	January 2021	Technical Requirements and Standard for Online Monitoring of Carbon Dioxide Emissions in Thermal Power Generation Enterprises	This standard is mainly aimed at the thermal power generation industry, which has a large proportion of carbon emissions. The direct monitoring method can be directly used to continuously monitor CO_2 emissions. A system including 'instructions, standards, and operation guarantees' can be established to manage GHG emission monitoring (Zhang et al. 2022)
CITIC Group	September 2021	Whitepaper of Carbon Peaking and Carbon Neutralisation Actions	The CITIC Group will strengthen carbon asset management, establish a comprehensive carbon information management system, and integrate related information such as carbon emission data and data related to carbon credit assets, carbon trading, and emission reduction projects to support carbon management analysis and decision making. The CITIC Group should also integrate 'double carbon' thinking into daily operation and management and promote the training, introduction, and reserve of professionals in the 'dual carbon' field (Wang 2021)

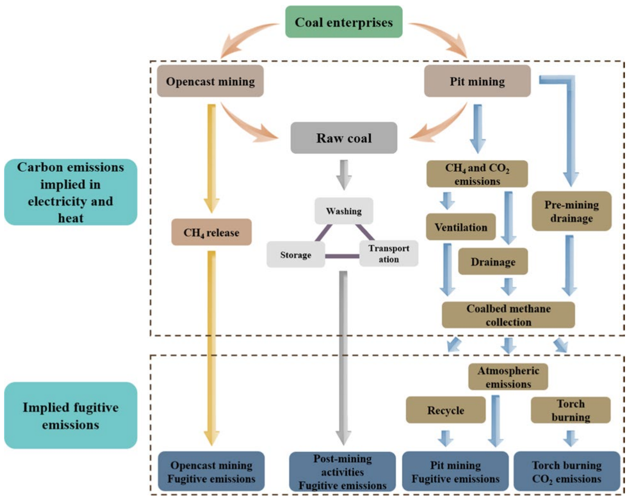

Fig. 4 Accounting boundaries of coal enterprises

reflect the environmental impacts of production activities of enterprises. Recently, the Ministry of Ecology and Environment issued and implemented the *Administrative Measures for Enterprises' Legal Disclosure of Environmental Information*, which focuses on the legal disclosure of environmental information by enterprises with large environmental impacts and significant public attention. The Measures also stipulate system construction, information sharing and reporting, supervision and inspection, and social supervision; clarify violations and corresponding penalties; and list the basic content of enterprises' legal disclosure of environmental information, such as the subject, content, form, time limit, and supervision and management. The Measures take enterprises' legal disclosure of environmental information as the basis for evaluating the corporate credit, strengthen the enterprises' main responsibility of ecological and environmental protection, and regulate the legal disclosure of environmental information (Wu and Wei 2022).

3.1 Carbon emission boundaries of coal enterprises

The carbon emissions of coal enterprises should be distinguished from the whole lifecycle of coal. It cannot be denied that coal is the leading source of carbon emissions. However, the carbon emissions from coal are concentrated in the combustion and utilisation of coal. Coal enterprises are engaged in coal mining and washing. Although coal enterprises have severe carbon emission behaviours in the production process, the proportion of such behaviours is smaller than that in the whole lifecycle of coal. Therefore, the boundaries should be clearly defined when the carbon emission responsibility of coal enterprises is divided.

The lifecycle of coal (An et al. 2016) consists of three stages: coal mining and washing, coal transportation, and coal consumption. The *Guidelines for Accounting and Reporting Greenhouse Gas Emissions of China's Coal Production* Enterprises stipulate the boundaries of coal production enterprises (Fig. 4). These boundaries include the basic production system, auxiliary production systems, and affiliated production systems that directly serve production. Auxiliary production systems include ventilation, extraction, transportation, lifting, and drainage systems, as well as power, power supply, heating, cooling, machine repair, warehouses, etc. in the factory. Affiliated production systems comprise the production command management system (factory headquarters) and the departments and units in the factory that serve production (e.g. staff canteens and workshop bathrooms) (Li 2021a, b).

The carbon emission sources of coal enterprises can be mainly divided into three categories: gas fugitive emissions, energy consumption emissions, and uncontrolled emissions. In the process of coal mining, the changes in the coal–rock strata lead to the discharge of the originally adsorbed carbon dioxide, methane, and other gases. The operation of mining equipment requires energy consumption, including raw coal, diesel, gasoline, electricity, water, and other resources. The types of resources required depend on the scenario. The produced raw coal and coal gangue inevitably release CO_2 during storage, but the CO_2 emissions in this case are less and slow. Therefore, this part of CO_2 emissions is not used as an accounting indicator alone.

3.2 Accounting method of carbon emissions of coal enterprises

Carbon emissions accounting mainly refers to converting GHG emissions into CO_2 equivalents. There are four commonly used methods for carbon emissions accounting: the onsite measurement method, material balance method, model decomposition factor method, and IPCC inventory method (Ouyang and Guo 2021).

(1) When the onsite measurement method is used, data are obtained from the onsite measurement of the emission source. This method requires long-term continuous monitoring via equipment. The data must be highly accurate. For achieving a high accuracy, data must be repeatedly collected and validated by relevant government departments. This method requires considerable labour and material resources.

(2) The material balance algorithm measures carbon emissions through a quantitative analysis of materials based on the law of conservation of mass. All factors in the process are considered. Although the consumption of labour and material resources is avoided, the original data of each

Table 5 Default values of the characteristic parameters of common fuels

Fuel type	Fuel category	Net calorific power (GJ/ton)	Carbon content per unit of calorific value (tC/GJ)	Carbon oxidation rate (%)
Solid fuel	Anthracite	24.515	27.49×10^3	94
	Bituminous coal	23.204	26.18×10^3	93
	Lignite	14.449	28.00×10^3	96
Liquid fuel	Gasoline	44.800	18.90×10^3	98
	Diesel fuel	43.330	20.20×10^3	98
	Kerosene	44.750	19.60×10^3	98
Gaseous fuel	Natural gas	389.310	15.30×10^3	99
	Coal gas	52.340	12.20×10^3	99

factor must be accurate and detailed. In addition, there are often uncertain factors in the actual operation process.

(3) The model decomposition factor method is obtained by deforming on the basis of the Kaya identity. Common methods include the AWD, LMDI, and IPAT decomposition methods. Such methods construct a coupling model between carbon emissions and various factors by quantifying various factors that affect carbon emissions. The results of the coupling model can provide a reference for the optimal design of carbon emission reduction; thus, the model is widely used in investment games.

(4) The IPCC inventory method is based on the *2006 IPCC National Greenhouse Gas Guidelines*. Most countries currently use this method to account for GHG emissions. This method calculates carbon emissions with regional or industry characteristics by establishing a comprehensive default calculation value and then designing specific emission factors based on the characteristics of different countries, regions, and industries.

According to the *Guidelines for Accounting Methods and Reporting of Greenhouse Gas Emissions of Mining Enterprises (Trial Implementation)* compiled by the National Centre for Climate Change Strategy Research and International Cooperation, the various carbon emission sources of coal enterprises are accounted for as follows:

$$E_{GHG} = E_{CO_2\text{combustion}} + E_{CO_2\text{carbonate}} - E_{CO_2\text{carbonisation}} + E_{CO_2\text{net electricity}} + E_{CO_2\text{net heat}} \quad (1)$$

where E_{GHG} represents the total GHG emission of coal enterprises; $E_{CO_2\text{combustion}}$ represents the carbon emission from fuel combustion; $E_{CO_2\text{carbonate}}$ represents the carbon emission from carbonate decomposition; $E_{CO_2\text{carbonisation}}$ represents the amount of CO_2 absorbed in the carbonisation process; $E_{CO_2\text{net electricity}}$ represents the carbon emission implied by the net purchased electricity; and $E_{CO_2\text{net heat}}$ represents the carbon emission implied by the net purchased heat.

The carbon emission of each factor is calculated as follows:

$$\begin{cases} E_{CO_2\text{combustion}} = \sum_i \left(AD_i \times CC_i \times OF_i \times 44/12\right) \\ E_{CO_2\text{carbonate}} = AD_{\text{ore}} \times \eta_{\text{ore}} \times \sum_j \left(PUR_j \times EF_j\right) \\ E_{CO_2\text{carbonisation}} = AD_{\text{carbonisation}} \times \sum_k \left(PUR_k \times EF_k\right) \\ E_{CO_2\text{electricity}} = AD_{\text{electricity}} \times EF_{\text{electricity}} \\ E_{CO_2\text{heat}} = AD_{\text{heat}} \times EF_{\text{heat}} \end{cases} \quad (2)$$

where i represents the fuel type, AD_i represents the consumption of fuel combustion, CC_i represents the carbon content of the fuel, OF_i represents the carbon oxidation rate of the fuel, 44/12 is the conversion coefficient between the molecular weights of CO_2 and carbon, AD_{ore} represents the calcined or roasted amount of ore, η_{ore} represents the decomposition rate of ore calcining and roasting, j indicates the type of carbonate contained in the ore, PUR_j represents the mass fraction of the carbonate, EF_j represents the CO_2 emission factor of the carbonate, $AD_{\text{carbonisation}}$ indicates the quality of the carbonised product, k denotes the carbonate component in the carbonised product, $AD_{\text{electricity}}$ represents the consumption of the net purchased electricity, $EF_{\text{electricity}}$ is the CO_2 emission factor of the electricity supply, AD_{heat} represents the consumption of the net purchased heat, and EF_{heat} is the CO_2 emission factor of the heat supply.

After introducing the default values of common parameters (Table 5), we can calculate the carbon emissions of specific coal enterprises.

4 Transformation direction of carbon storage in abandoned mines

Guided by policies, implementing corporate development plans, changing traditional thinking paths, and reflecting corporate social value, coal enterprises should seize the

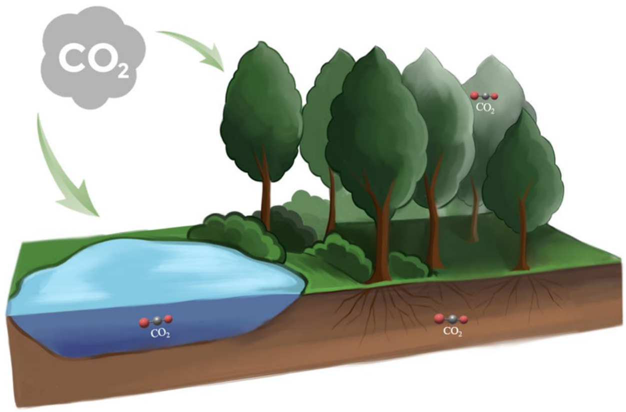

Fig. 5 Carbon storage of the ecosystem

trump card of abandoned mines and occupy a corner of the carbon trading market. Recently, the State Council of China issued the *Carbon Peaking Action Plan by 2030*. As a policy document that stipulates the leading role of N in the carbon peaking and carbon neutrality "1 + N" policy system, this Action Plan is the overall deployment of the carbon peaking stage and classifies, materialises, and concretises relevant indicators and tasks (Hou et al. 2022). It provides a basis for all industries to deploy feasible carbon peaking action plans. There are two ways to achieve the goal of carbon neutrality, including four paths. One is to control and reduce carbon emissions, which can be achieved by carbon reduction and carbon replacement; the other is to promote and increase carbon absorption, which can be achieved by carbon absorption and carbon storage.

However, reducing carbon emissions can only delay carbon peaking; it cannot achieve the ultimate carbon neutrality goal. Therefore, using the space resources remaining in abandoned mines to implement carbon storage is the first step for coal enterprises to avoid the predicament (Lyu et al. 2022).

4.1 Ecological carbon sinks of abandoned mines

Ecological carbon sinks generally refer to the carbon storage capacity of natural ecosystems such as grasslands, green spaces, forests, wetlands, oceans, and soils (Fig. 5). Ecological carbon sinks can be roughly divided by their subjects into three categories: vegetation carbon sink, soil carbon sink, and water carbon sink.

According to the research results of a key consulting project entitled 'Research on the Efficient Recovery and Energy-Saving Strategy of Coal Resources in China' of the Chinese Academy of Engineering (Yuan et al. 2018), the land area of abandoned mines in China is approximately 56,160 km^2, the area per mine can reach 30 km^2, and the collapsed area can reach 0.37 km^2 per mine. These figures are increasing annually. With the efforts to achieve carbon neutrality goals, the number of abandoned mines is bound to increase rapidly.

Restoring the ecological environment according to local conditions is the most direct way to manage and utilise abandoned mine land. Afforestation and greening projects can be conducted on relatively flat ground, and water (e.g. lakes) is stored in the collapsed area of abandoned mines to form a multimode ecological construction project for abandoned mines. This measure can provide the society with timber and various forest by-products, take advantage of the tax deduction policy, and increase the scale of ecological carbon sinks, making it possible to exploit new opportunities in the carbon sink market.

Global forest ecosystems store 76%–98% of organic carbon in terrestrial ecosystems. From 1990 to 2007, the global forest carbon sink was approximately 2.4 ± 0.4 PgC per year. From 1982 to 2008, China's forest carbon sink reached 0.02 PgC per year, with a total of 1.65 ± 0.76 PgC corresponding to the forest biomass carbon pool (Bian et al. 2022). According to the unified national carbon trading market standard, trees absorb 1.83 tCO_2e per cubic metre, and the carbon storage of adult trees per square kilometre is approximately 22,580.65 tCO_2e. The carbon sink can be calculated using the stand volume method:

$$S_{CO_2} = V_t \times \delta \times \theta \times \gamma + \varphi(\delta \times \theta \times \gamma) + \mu\left(V_t \times \delta \times \theta \times \gamma\right) \quad (3)$$

where S_{CO_2} represents the total amount of carbon stored in forests, V_t represents the forest storage capacity, δ is the biological expansion coefficient, θ represents the forest bulk density, γ represents the carbon content, φ is the conversion coefficient of carbon storage for understory plants, and μ is the conversion coefficient of forestland carbon storage.

The terrestrial soil is the largest carbon pool on Earth's surface. The global soil carbon pool reaches 2.2×10^3 to 3×10^3 PgC, which is two to three times the vegetation carbon pool and twice the global atmospheric carbon pool. China's soil carbon pool stores 102.96 billion tons of carbon (Liu and Xu 2022). The carbon density varies significantly with respect to the soil properties. Typically, the soil carbon density can be calculated as follows:

$$\mathrm{SOC} = tbO(1 - V) \quad (4)$$

where SOC represents the soil carbon density, t represents the thickness of the soil layer, b represents the soil bulk density, O represents the organic carbon content of the soil, and V represents the volume ratio of gravel with a diameter of > 2 mm in the soil.

The ocean is the main source of water carbon sinks. The carbon storage capacity of the ocean is approximately 4000 trillion tons, with an annual storage capacity of approximately

500–600 million tons. However, freshwater lakes mainly rely on internal soil silt, algae, and microorganisms for carbon storage, and they have less carbon absorption. Therefore, the carbon storage effect of freshwater lakes is not considered in the ecological environment of abandoned mines.

4.2 Carbon storage of saline aquifers in abandoned mines

Underground saline water refers to groundwater with a salinity of ≥ 2.0 g/L. China has a large volume of saline aquifers. Deep saline water has no other uses at present. Most of it is characterised by high salinity and cannot be used to form an economical product. Therefore, deep saline water is suitable for CO_2 storage. CO_2 dissolved in water is bound by capillary force and passively stored in the saline aquifers. Here, it chemically reacts with saline water to generate minerals such as calcium carbonate salts, increasing the storage capacity.

$$\begin{cases} 2NH_4OH(aq) + Ca(NO_3)_2\,(aq) + CO_2(g) \rightarrow (NH_4)_2CO_3(aq) + Ca(NO_3)_2(aq) + H_2O \\ (NH_4)_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2NH_4NO_3(aq) + CaCO_3 \end{cases} \tag{5}$$

The CO_2 storage capacity of inland saline aquifers in China has reached 14.35 billion tons (Li et al. 2006). In theory, saline aquifers can store 0.23–0.31 tons of CO_2 per cubic meter. The main factors affecting the carbon storage capacity of a saline aquifer are its depth, porosity, permeability, and salinity (Fig. 6). The actual storage capacity of the saline aquifers can be calculated as follows:

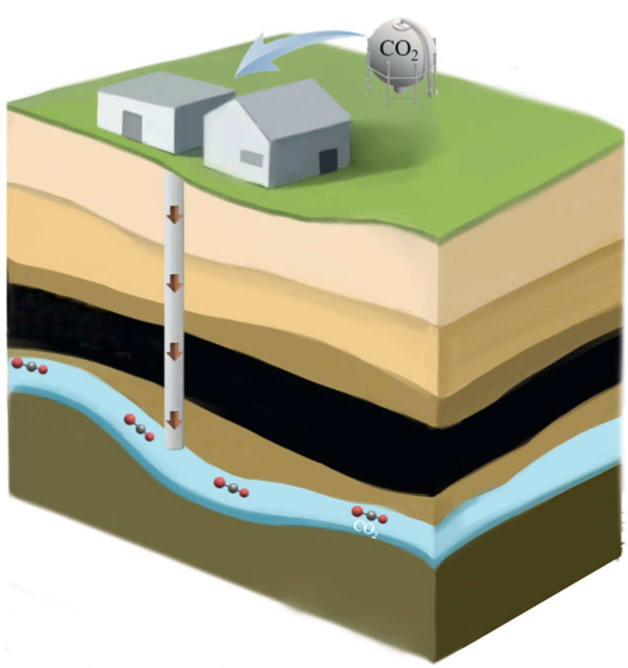

Fig. 6 Carbon storage of underground saline aquifers

$$M_{CO_2} = a \times A \times h \times \phi \times \rho_{CO_2} \times S_{eff} \times (1 - S_{wirr}) \tag{6}$$

where M_{CO_2} represents the actual storage capacity of the saline aquifers, a represents the ratio of the area of the saline aquifers to the evaluation area, A represents the to-be-evaluated area, h represents the average thickness of the saline aquifers, ϕ represents the average porosity of the saline aquifers, ρ_{CO_2} represents the average density of CO_2, S_{eff} is the storage coefficient of the saline aquifers, and S_{wirr} represents the minimum water content of the pores.

4.3 Carbon storage of coal–rock strata in abandoned mines

Carbon storage of the coal–rock strata refers to a process in which CO_2 is stored in the pores and fissures of underground rock formations (Fig. 7). In this process, the adsorption characteristics of coal-bearing rocks for CO_2 are exploited to achieve efficient and stable storage. In coal–rock strata, the adsorption capacity of CO_2 can reach about two to three times that of CH_4, and the CO_2 in the supercritical state can reach 10 times the adsorption capacity of CH_4 (Wang et al. 2022). After an abandoned mine is mined, most of the originally adsorbed CH_4 in the remaining coal seams and broken rock layers has gushed out, providing space for the adsorption of CO_2. Thus, the coal and rock masses in the broken state have more pores and fissures, which lead to a higher permeability and better carbon storage effect.

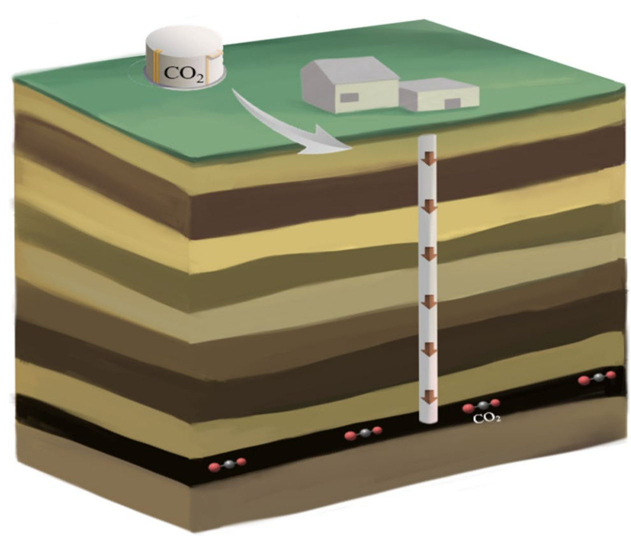

Fig. 7 Carbon storage of underground coal–rock strata

The volume of underground space in abandoned mines in China has reached 7.2 billion cubic metres, and it is increasing with the advancement of the 'dual carbon' goal. Per cubic metre, coal mass can store 0.25 tCO_2e on average. The adsorption capacity of broken rock mass is approximately half of that of coal mass. Per cubic metre, rock mass can store 0.13 tCO_2e. The actual storage volume of broken coal and rock masses in the underground space of abandoned mines is given as follows:

$$D_{CO_2} = Q \times H \times \rho_{coal} \times RF \times C \tag{7}$$

where D_{CO_2} represents the actual amount of carbon stored in the underground space, Q represents the storage area, H represents the thickness of the coal–rock strata, ρ_{coal} represents the apparent density of the coal mass, RF is the recovery factor, and C represents the space ratio of the coal and rock masses.

4.4 Mineralised carbon storage in abandoned mines

Mineralised carbon storage refers to a process in which CO_2 reacts with the mineral components of the formation rock, leading to stable solid crystalline precipitation. This type of storage is the optimal way to achieve permanent CO_2 storage (Liu et al. 2021). The type of reaction and the reaction rate depend on the mineral compositions of the rock formations. At present, olivine, serpentine, and wollastonite are mainly used for research on mineralised carbon storage, and the factors affecting CO_2 mineralisation mainly include the reaction temperature, reaction pressure, and particle size of raw materials for mineralisation. Minerals can store 0.89 tCO_2e per cubic metre on average. However, because the mineralised storage process often lasts for decades or even centuries, the annual carbon storage amount is often used for evaluation. Per unit cubic metre, minerals can store approximately 1.17×10^{-4} tCO_2e per year, which can be given as

$$F_{CO_2} = M \times L \times 2 \times (C_{Fe} + C_{Ca} + C_{Mg}) \tag{8}$$

where F_{CO_2} represents the actual volume of mineralised carbon storage; M represents the area of mineralised storage; L represents the annual leaching volume; and C_{Fe}, C_{Ca}, and C_{Mg} represent the average contents of Fe^{2+}, Ca^{2+}, and Mg^{2+}, respectively, in the leachate.

5 Analysis of transformation scenarios for coal enterprises

To achieve sustainable green resource development and carbon neutrality as soon as possible, the Chinese government has launched carbon emission trading across the country to build a unified carbon trading market. The government actively allocates carbon emission allowances to different industries and enterprises in different regions. Enterprises can sell the remaining carbon emission allowances after meeting their production and operation needs, purchase carbon emission rights to meet their production and operation needs, or participate in carbon emission reduction projects in China and abroad to obtain deductible carbon emission allowances. The implementation of carbon emission trading can not only achieve low carbon and emission reduction of enterprises but also provide a new direction for corporate profits.

In addition, many countries and regional organisations have proposed targeted carbon tax policies and related carbon subsidies and incentive regulations. China will launch a carbon tax policy at an appropriate time and collect carbon taxes from the production link first and eventually from the consumption link. Many provinces and cities have released support measures for energy conservation and carbon reduction. In the future, coal enterprises are bound to face the high cost of carbon emissions and the precarious situation of their social image. Therefore, the rational use of abandoned mines to realise the transformation and development of carbon storage is a key measure for enterprises to achieve long-term economic growth, improve their social value, and increase their hidden profits.

5.1 Scenario analysis of coal enterprises under carbon emission allowances

Two main carbon emission allowance allocation methods are used in the world: the free allocation method and the auction method. At present, China primarily adopts free allocation. Although the auction method is applied in some areas, the proportion of such areas is extremely small. For example, Guangdong Province used the free allocation method for 97% of the cases and the auction method for 3% of the cases in the past and has now abolished the auction method. Therefore, the internal carbon verification and carbon disclosure of an enterprise are important, as they determine the free allowances that the enterprise can obtain.

We take a mine in Shanxi Province as an example. The production capacity of this mine was 4.8 million tons in 2016. According to preliminary calculations, the mine consumed 1,725,253 tons of water resources; 35.2 tons of diesel oil; 46.31 tons of gasoline; 89,163.77 MWh of electricity; and 5,846.11 tons of raw coal during production, and it consumes 586,370 tons of water resources; 140.58 tons of diesel oil; 39.52 tons of gasoline; and 31,532.76 MWh of electricity during the coal washing process. According to the method of accounting for carbon emissions of coal enterprises, the total CO_2 emission from mining and washing in the mine was calculated as 409,239.4 tCO_2e. However, the

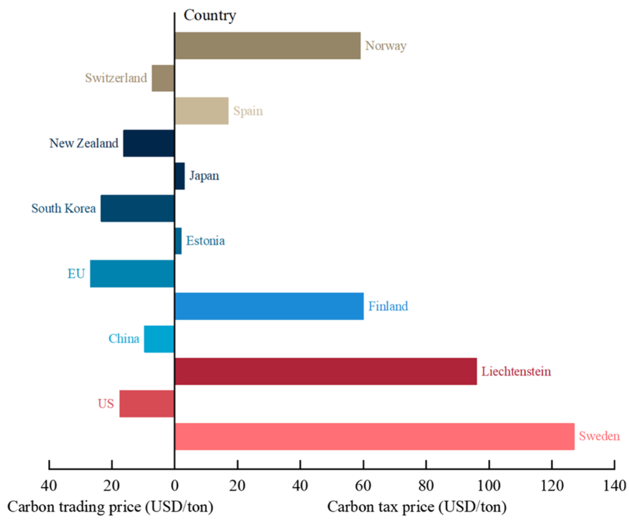

Fig. 8 National carbon trading and carbon tax prices

approved production capacity of coal enterprises in Shanxi Province was 941.2 million tons in 2016, and the carbon emission allowance in Shanxi Province was 0.591×10^8 tCO_2e in 2017, exhibiting a gap as large as 8.528×10^8 tCO_2e. The mine accounted for 0.6925% of the annual emissions, while its production capacity only accounted for 0.5099% of the approved coal production capacity.

The carbon emission allowances of coal enterprises are clearly insufficient. Even if the optimal conditions are considered (i.e. coal enterprises are given priority and equal allowances are allocated), the mine needs an additional CNY 22.8749 million to purchase carbon emission rights, which was calculated using the carbon trading price of 59.77 CNY/ton (the average daily minimum price of carbon trading in April 2022). According to the thermal coal market price of 675 CNY/ton (the coal price in April 2022), the net profit is approximately CNY 224 million. Therefore, the loss of profit is nearly 10.23%.

5.2 Scenario analysis of coal enterprises under carbon taxation

Carbon tax refers to a tax levied on CO_2 emissions, which urges taxpayers to reduce carbon emissions. The cost of establishing a carbon tax system is relatively small, and China's current tax supervision system is relatively mature. Carbon emissions trading involves a punishment for exceeding the basic emissions, while the carbon tax is levied to regulate the overall carbon emissions. Therefore, these two methods must be coordinated to avoid repeated punishments for enterprises.

We investigated the current implementation level of carbon tax in various countries. Sweden has conducted carbon tax reform since 1991, and the tax burden of CO_2 is limited to 1.7% of the output value; however, it is maintained at approximately 1.2% in the implementation process. In Denmark, the carbon tax is approximately 2.0%–12.5% of the sales, and the tax is paid in different gradients. Australia, the US, and Japan adopt a fixed tax payment method; each ton of CO_2 is charged approximately 10–70 US dollars, and the tax depends on the industry. According to China's national conditions and the general conditions of various countries, China sets the carbon tax at approximately 8.1–377.6 CNY/ton, which is converted from the international currency (Fig. 8).

The aforementioned mine in Shanxi Province is again taken as an example. We use 675 CNY/ton (the coal price in April 2022) as the thermal coal market price, consider the minimum carbon tax as approximately 8.1 CNY/ton, and take the approved production capacity as the trading volume. Calculation results indicate that the annual tax paid is approximately CNY 38.88 million and that the loss of profit is approximately 17.39%. Considering the comprehensive effect of the carbon tax and carbon trading, the cost per ton of coal increases by CNY 12.87, and the annual profit of the enterprises decreases by 27.62%.

5.3 Scenario analysis of transformation and development of abandoned mines

Owing to the different conditions of abandoned mines in different regions, we assume that both the average mining height of coal seams and the thickness of underground saline aquifers are 5 m and calculate the basic amount of carbon storage of various types according to the unit area for abandoned mines (30 km^2) (Table 6).

For different carbon storage methods, the costs of carbon capture, transportation, and storage in different pathways should be considered (Fig. 9).

Taking wasteland planting as an example, the planting of 5550 trees per square kilometre requires an average

Table 6 Carbon storage types

Storage type	Ecological storage	Storage in saline aquifer	Storage in coal–rock strata	Mineralised storage
Annual carbon storage (tCO_2e)	677,419.5	34,500,000	28,500,000	17,550
Carbon trading value (CNY10,000)	4048.94	206,206.5	170,344.5	104.90

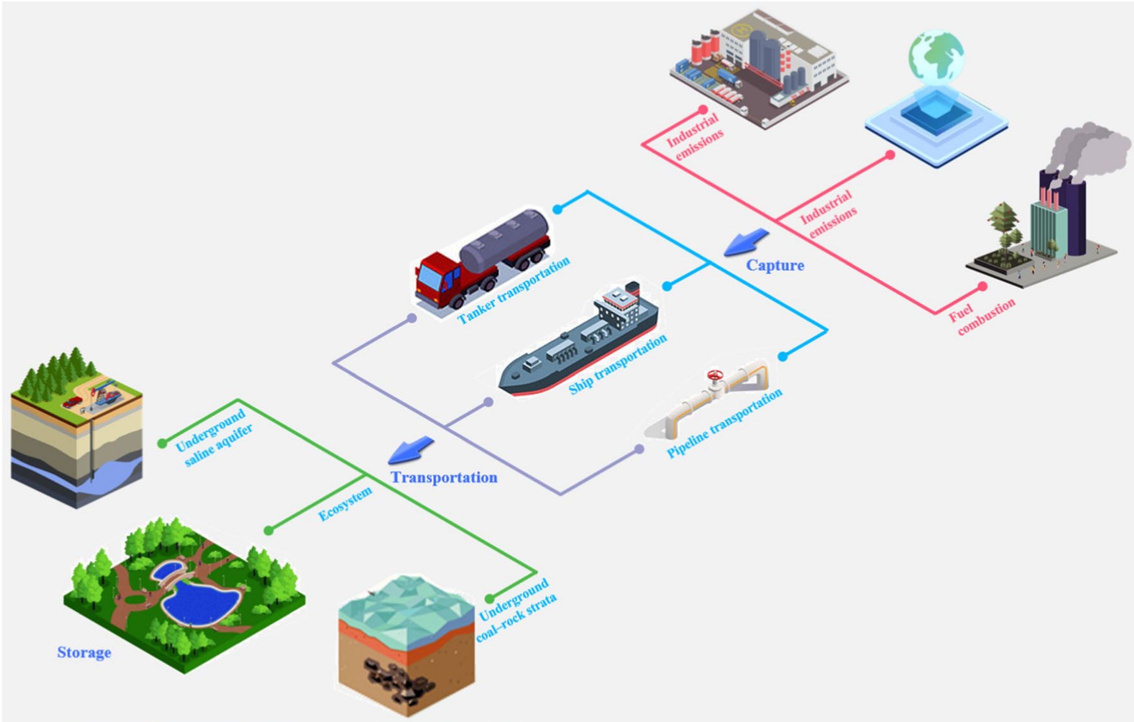

Fig. 9 Carbon capture, transportation, and storage pathways

Table 7 Carbon storage scenarios

Parameter	Carbon trading and taxation	Carbon storage cost	Ecological storage revenue	Saline aquifer storage revenue	Coal–rock strata storage revenue	Mineralised storage revenue
Gross value of Scenario I (in CNY10,000)	67.87	145	4540.38	– 266,098.5	– 219,820.5	– 135.36
Gross value of Scenario II (in CNY10,000)	437.3	145	4540.38	1,008,435	833,055	512.99
Gross value of Scenario III (in CNY10,000)	67.87	60	4540.38	27,151.5	22,429.5	13.81
Gross value of Scenario IV (in CNY10,000)	437.3	60	4540.38	1,301,685	1,075,305	662.16

investment of 6750 CNY/km^2 for land preparation; an average investment of 1387.5 CNY/km^2 for seedlings; a planting cost of 1500 CNY/km^2; and a fertilisation cost of 2250 CNY/km^2. The planted trees must be cultivated for three consecutive years, with a total cost of 7200 CNY/km^2. Overall, CNY 572,625 per unit area (30 km^2) of abandoned mines must be invested.

Shenhua Group's 300,000-ton coal-to-liquid high-concentration CO_2 capture and storage technology development demonstration project has been successfully operated in China (Zhao et al. 2017). A total of CNY 210 million has been invested in infrastructure construction, and the storage cost of each ton of CO_2 in the later stage of operation is approximately CNY 117–135. Because the equipment is expected to operate for 25 years, the total cost of CO_2 storage per ton per year is CNY 145–163.

We see from the current market price of carbon trading that the carbon storage projects are of low economic efficiency. However, considering the development law of carbon trading prices in various countries, there is considerable room for improving the carbon trading prices in China. With the development of technology, the cost of carbon storage will gradually be reduced; thus, coal enterprises should start adjusting their corporate structures (Table 7).

At present, the optimal method for carbon storage in abandoned mines is to plant trees and promote the construction of underground carbon neutrality infrastructure. Carbon storage projects will bring not only carbon trading revenues but also hidden benefits to enterprises.

For example, environmental protection projects stipulated in the Regulations on the Implementation of the Enterprise Income Tax Law of the People's Republic of China are exempt from corporate income tax from the first year to the third year (Qiu and Peng 2022); the *Circular of the Ministry of Finance and the State Administration of Taxation on Comprehensively Launching the Pilot Program of Replacing Business Tax with Value-Added Tax* stipulates that energy-saving service companies will temporarily be exempted from paying value-added tax for various projects; the *Announcement on Issues Concerning the Income Tax Policy of Third-Party Enterprises Engaged in Pollution Prevention and Control* stipulates that an enterprise income tax at a rate of 15% is imposed on third-party enterprises engaged in pollution prevention and control.

In addition, there are currently 89 carbon neutrality bonds in China, with a total issuance scale of CNY 104.64 billion. Shanghai Xuhui District issued a special fund management method for energy conservation and carbon emission reduction and rewarded emission reduction enterprises with CNY 3 million. Jiangsu Province implements a fiscal policy that is linked to the effect of pollution and carbon reduction, whereby 10% of the total pooled funds are rewarded to localities with excellent performance. Beijing will reward enterprises with a maximum of CNY 30 million for pollution control and low-carbon development. Hangzhou will reward enterprises who make equipment investments focusing on the research of green low-carbon technology, pollution and carbon reduction technology, and carbon negative emission technology with CNY 5 million. Shenzhen Bureau of Industry and Information Technology provides subsidies of CNY 10 million to enterprises that have reached peak carbon emissions.

Therefore, coal enterprises' transformation of abandoned mines should not just rely on their own strength. These enterprises should also coordinate with local and regional governments to promote the realisation of local carbon neutrality goals and use national policies to leverage market investment, reduce project risks, and promote industrial implementation. In this manner, a win–win model combining corporate revenues and government actions can be formed.

6 Suggestions for carbon storage transformation of abandoned mines

The transformation and construction of carbon storage in abandoned mines of coal enterprises cannot be achieved overnight and will encounter many problems in industrial implementation and scientific research and development. It is not only related to the existing conditions of abandoned mines but also involves the support of the government and industry. In addition, it will face the screening of the market economy and social development. Therefore, it is necessary to coordinate efforts from multiple parties and take multiple measures to promote the transformation and development of carbon storage in abandoned mines.

6.1 Improving construction of new resource structure

CO_2 has long been criticised as a source of environmental pollution. However, it is necessary to establish the concept of new resource development and determine how to store and use carbon in the context of the new era.

The government should enact the relevant laws and regulations as soon as possible and promote the legislation of carbon taxes and the issuance of carbon subsidy policies while opening the market. For supporting scientific research on carbon neutrality, the government should increase support for the development and transformation of innovative enterprises and traditional enterprises and clarify the legal relationship between heavily polluting enterprises and their subordinate carbon storage and utilisation enterprises. Government departments should be set up to verify and supervise the carbon emission information of enterprises, reaffirm the correct social value of enterprises, and tie carbon emissions to corporate image. It is also necessary to establish a carbon credit system for bank lending decisions.

6.2 Collecting statistics on carbon storage in abandoned mines

The census of carbon storage information of abandoned mines is not only a survey of the basic situation but also an inspection of the uncertain carbon emission factors of coal enterprises. The establishment of a large database for abandoned mines can satisfy the information inquiries of the nation and enterprises and provide a foundation for the transformation of carbon storage.

Carbon neutrality does not imply the self-realisation of enterprises and industries but the simultaneous coordination of regions, localities, and the nation to take advantage of abandoned mine resources nationwide and master basic decision-making information. Following the program of achieving a carbon-negative status for different regions, driving local carbon neutrality, and reducing national carbon emissions, China will focus on the development of carbon storage in abandoned mines in advantageous areas, stimulate the rapid development of the carbon trading market, and provide fertile ground for the implementation of a wider range of carbon storage and utilisation projects.

6.3 Ensuring technological development and talent cultivation

Science and technology are the primary productive forces, and talent is the driving force of the industry. The emergence of new methods and new theories is bound to produce an attractive and false impression. The process of turning methods into practices and theory into reality requires continuous in-depth scientific research and groups of enthusiastic and talented individuals.

The government, enterprises, and universities must emphasize the development of carbon neutrality technology, clearly understand the value and goal of carbon neutrality, formulate a systematic and comprehensive scientific research training system, and enact incentive policies at all levels. Regarding enterprises' actions, it is necessary to build a bridge connecting the industry, universities, research, users, and finance, use projects to force the development of science and technology, improve project management, and coordinate the progress of projects and technologies.

7 Conclusions and prospects

(1) The carbon neutrality goal is not only a national strategic layout but also an inevitable trend of social progress. The '30·60' goals are imminent. Given its tremendous responsibilities, China must learn from its past experience and other countries to improve its system while giving full play to its national characteristics. It is necessary to strictly supervise the disclosure of carbon information, understand the crisis and industry prospects of coal enterprises, and clarify the boundaries of coal enterprises in the whole lifecycle of coal according to the actual situations of coal enterprises.

(2) Aboveground and underground carbon storage in abandoned mines should be planned. It is recommended to obtain new knowledge and develop new theories. The carbon storage capacities of vegetation and soil can be used to achieve carbon storage in abandoned spaces and redevelopment of legacy resources. It is also necessary to understand the transformation and development direction and potential of carbon storage.

(3) It is advisable to investigate the development dilemma of coal enterprises through scenario cases. Transformation prospects can be developed using theoretical knowledge to promote the transformation and construction of carbon storage in abandoned mines. Additionally, coal enterprises are recommended to actively trade in the carbon sink market. This helps to achieve win–win cooperation between enterprises and local governments.

(4) Three suggestions, i.e. the improvement of resource structure, census of existing information, and talent and technology training, are proposed to standardise the order of the existing carbon storage market, specify the direction of enterprise transformation and development, emphasise the overall planning of basic information, and provide technical benefits.

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Declarations

Conflicts of interest The authors declare no conflict of interest.

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