CONSTRUCTION PATHWAYS FOR CARBON-NEUTRAL COAL MINES IN THE MIDDLE REACHES OF THE YELLOW RIVER BASIN: A CASE STUDY OF THE YONGNING COAL MINE IN SHANXI PROVINCE

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Abstract. Coal mining parks in the Yellow River Basin are tasked with driving high-quality economic development, yet they simultaneously act as significant energy consumers and carbon emitters. Consequently, the development of carbon-neutral coal mining parks is crucial for China to achieve its 2030 carbon peaking and 2060 carbon neutrality goals ("Dual Carbon" goals). This paper explores pathways toward carbon neutrality transition and carbon neutrality at the coal mining park level, using the Yongning Coal Mine as a case study. It discusses control measures for developing a carbon-neutral coal mining park and proposes three strategies: carbon offset, a self-balancing carbon model, and market incentives. While the cost-effectiveness of purchasing carbon offsets remains limited, the study recommends prioritizing emission reduction efficiency, enhancing carbon sinks, optimizing ecological restoration patterns, and comprehensively promoting clean energy to balance the carbon budget.
Keywords: *carbon sink, ecological restoration, carbon neutrality, land use change, Yongning coal mine*

Introduction

Global climate change and ecological environment changes have made carbon neutrality a critical research focus in international energy conservation and sustainable development, as well as a core responsibility for nations in balancing economic growth and environmental protection. This is especially reflected in the speech made by President Xi at the United Nations General Assembly on September 22, 2020, committing China to peak carbon emissions before 2030 and achieve carbon neutrality by 2060. This pledge underscores China's role as a major developing nation in global environmental stewardship and sets new requirements for the carbon neutrality transition of high-carbon industries. Carbon-neutral development, rather than "low-

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carbon" approaches, has become the inevitable path for China's sustainable and integrated progress.

As the region with the largest scale of coal development in China, the Yellow River Basin is a high energy-consuming and high-carbon emission area in the country. The ecological protection and high-quality development of the Yellow River Basin is a "millennium strategy for China's great rejuvenation". The environmental pollution control in the mining areas is the fundamental way to promote the high-quality development of the Yellow River (Miao et al., 2025; Peng et al., 2020; Wang et al., 2021). As a major coal development province in the Yellow River Basin, Shanxi Province is comprehensively advancing coal mining transformation through reduction, optimization, and greening, with the proportion of high-quality production capacity reaching 68% (Mo et al., 2021). The "Trial Measures for the Administration of Carbon emission allowances Trading" released on February 12, 2021, marks that carbon emissions will be directly linked to the economic benefits of enterprises. The increase in carbon prices will force enterprises to reduce carbon emissions. Thus, achieving carbon neutrality—not "net-zero emissions"—is an inevitable trend for coal mining parks, while meeting environmental and economic goals.

At present, in scholars' research on carbon-neutral development, it mainly focuses on key components of the carbon cycle: carbon source, carbon sink and carbon cycle. In the research of carbon sources, two main perspectives are adopted: macroscopic and microscopic. Macro studies mainly take cities or regions as the research objects, exploring the relationship between carbon reduction and regional GDP development. Factors such as production methods, urbanization, and energy structure all have an impact on overall carbon emissions (Song et al., 2009; Zhu et al., 2009; Zhang et al., 2015). At the micro scale, high-tech industrial parks in developed regions are often taken as the research objects, and it is proposed to optimize the industrial structure through methods such as industrial symbiosis and clean energy to increase efficiency and reduce carbon emissions (Trevor et al., 2016; Yu et al., 2015; Zhang et al., 2015; Feng et al., 2018). In carbon sink research, forest ecosystems have attracted much attention due to their obvious cost-benefit advantages: most scholars analyze the dynamic changes of carbon storage in different forest stands from the perspectives of ecology and soil science, and explore how different climate and soil zones, dominant tree species, population composition, tree age and other factors affect the carbon sequestration efficiency of forest land, providing a theoretical basis for forest carbon sequestration (Newell et al., 2000; Pan et al., 2011; Fang et al., 2015). Meanwhile, with the rise of carbon trading, carbon sink circulation and circulation efficiency have gradually become research hotspots (Cao, 2018).

Coal mining parks are transitioning from extensive to high-quality development. Especially under the guidance of President Xi's ecological civilization thought—specifically the concept that "Lucid waters and lush mountains are invaluable assets" for green development and the promotion of existing resources, abandoned industrial and mining land and inefficient construction land have increasingly become important means for the development and transformation of mining enterprises. Many scholars have made significant contributions to increasing the survival rate and greening efficiency in the field of mine ecological restoration by using plant roots as ecological support for slope stabilization or by domesticating plants through soil improvement and mycorrhizal introduction. They have also provided an ecological foundation for the reclamation and comprehensive utilization of coal mining subsidence areas, significantly enhancing ecological and social benefits (Bi et al., 2020; Peng et al., 2020; Bai et al., 2006, 2001;

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Yuan, 2018). However, carbon sequestration in mining areas remains disconnected from holistic park-level carbon neutrality planning.

Therefore, with the overall goal of establishing a carbon-neutral mining industrial park, a holistic approach is required, integrating the concepts of carbon sources and carbon sinks with the achievements of ecological restoration. On the premise of not compromising its own development and revenue, achieving a carbon-neutral coal mining park is of paramount importance for the low-carbon transformation of the traditional high-carbon coal mining industry. This paper aims to analyze the carbon cycle status of coal mining parks in the Yellow River Basin, using management and technology as two key levers and considering both short-term and long-term benefits, to propose an optimal comprehensive carbon reduction strategy for the ultimate realization of a dynamically carbon-neutral mine.

Materials and methods

For many years, the carbon-neutral construction of coal mining parks has mainly been carried out within the narrow concept of mining areas, that is, small areas of industrial sites centered on coal production operation zones. This kind of carbon-neutral construction in mining areas in a narrow sense clearly fails to meet the requirements of the new era for "overall protection, systematic restoration and comprehensive governance" in accordance with river basins or regions.

With the expansion of the influence range of coal production points, lines, above-grounds, and networks, objectively, a complex area has been formed among coal mines, rural areas, and cities, including three types of complex areas: mine-agriculture, mine-urban, and mine-agriculture-urban. It seems that the coal production on the ground has boundaries, but in fact, its influence extends to all areas within the boundaries of the mining fields. The boundary of the coal mining parks studied in this article is defined by the boundary of the mining field. It refers to a community of production, life, and environment where underground coal mining activities, various coal-related production activities on the ground and the utilization of various biological resources are the main forms of industrial development. Within and among each system, there exists material circulation and energy flow, and they are interdependent. In addition, the carbon-neutral evaluation standard is an evaluation system developed based on meeting the environmental protection evaluation standards for coal mines in China. Therefore, what this article attempts to explore is how to achieve the carbon-neutral development of the area within the coal mine field and realize the goal of a carbon-neutral industrial park by meeting the relevant environmental quality assessment standards and emission standards in the ecological construction of mines.

Case overview

This article takes the Yongning Coal mining park in Lishi, Luliang, Shanxi Province as a typical case for research. This mine has an annual output of 900,000 tons, which is of medium scale. It has passed the environmental impact assessment. It is located in the northern part of Lishi District, Luliang City, 12 kilometers away from Lishi District. The main land use types within the mine field area are mining, agriculture, forestry, and villages. This industrial park has established a complete underground coal industrial chain, covering the entire process from coal mining to transportation, processing, and utilization, and features typical characteristics of the industry.

Concepts and boundaries

Research published since the IPCC's assessment in 2007 has confirmed that carbon neutrality plays a significant role in controlling carbon emissions and mitigating global warming. Carbon neutrality implies balancing carbon emissions with carbon removal within a specific boundary (Zhu, 2020). For the current energy structure in China, new energy sources cannot completely replace traditional coal in the short term. Coal mining will remain an important part of ensuring social livelihood for a considerable period. Unlike high-end industrial parks in developed regions, energy consumption plays a significant role in the economic development of coal mining parks. However, it is unrealistic for strict carbon-neutral emissions to restrict the economic development of industrial parks, which is due to the increase in energy costs. Unlike in this study, carbon-neutral emissions at the industrial park level aim to achieve net zero-carbon emissions, which can be described by *Equation 1*:

$$C_{tot}^{NZCP} = \int_0^T (C_{above}(t) + C_{under}(t) - C_{min}(t))dt + C_S - C_c \leq 0 = \int_0^T (C_{mf}(t) + C_{lg}(t) + C_{et}(t) - C_{mp}(t) - C_{wd}(t) - C_{fl}(t))dt + C_S - C_c \leq 0 \quad \text{(Eq.1)}$$

Among them, $C_{above}(t)$ refers to the carbon emissions of the ground production system. $C_{under}(t)$ denotes the volume of underground carbon source escape during the mining process. $C_{min}(t)$ represents negative carbon emission behaviors such as ecological reclamation, carbon dioxide capture and storage, reclamation carbon sinks or carbon dioxide capture and storage. $C_{ms}(t)$, $C_{pf}(t)$ and $C_{vg}(t)$ respectively represent the carbon dioxide produced by mining enterprises during the production process, by the lives of workers and residents within the coal mine field, and by the environment. C_S is the carbon offset volume generated by the coal park that is sold to a third party or other entity, C_c means the carbon offset entity purchased from a third party or other party.

Generally speaking, the boundaries of carbon emissions include temporal boundaries and spatial boundaries. The main purpose of defining the time boundary is to set a starting point for tracking carbon emissions and facilitate the determination of the average duration of monitoring emissions. From the perspective of the entire life cycle of the carbon cycle, the calculation of carbon emissions includes the establishment stage, mining stage and shutdown and demolition stage of carbon-neutral coal mines. However, for the carbon reduction aspect of a coal mining park, the mining period is the stage when carbon emissions are most concentrated, and the emission boundary is mainly concentrated at the mining boundary. The starting point of the time boundary is confirmed when the industrial park is completed. The average duration of monitoring emissions is an important factor affecting emissions in an industrial park, as irregular emission activities and the supply of renewable energy have seasonal fluctuations. Therefore, in this model, carbon balance can be evaluated over a period of one year to avoid seasonal fluctuations. Since the actual affected area of mining is the mining field range, the spatial boundary is based on the mining field boundary. All the terms in *Equation 1* are within the boundaries of the mining field.

Construction of carbon-neutral coal mines

In terms of the overall framework, first, coal mining parks should be based on local policies and economic development needs. Subject to meeting environmental assessment

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standards, with the goal of "carbon-neutral coal mines", the status of carbon emissions is analyzed, including carbon source analysis and carbon sink analysis of the coal mining park. Based on the main influencing factors of carbon emissions, this paper mainly analyzes the production mode, power, and energy consumption mode, as well as the public services within the mining field and the surrounding residential areas. In terms of carbon sinks, the focus is on the status of various land types such as forests, shrubs, farmlands, and grasslands within the mining field, as well as the ecological restoration green spaces like green parks and waste dumps within the industrial square. Based on the current carbon imbalance in coal mining parks, through comprehensive benefit evaluation, comprehensive management measures and technical measures are provided for carbon reduction. The management measures mainly focus on energy management and monitoring energy consumption and carbon emissions. The technical strategy aims to achieve a balance between energy supply and demand as well as carbon emissions. The actual effects of these measures will be evaluated once a year after their implementation. If coal mining parks still fail to achieve carbon neutrality, management and technical measures will be employed again to approach the carbon-neutral goal. As shown in *Figure 1,* the industrial structure diagram illustrates the proposed framework.

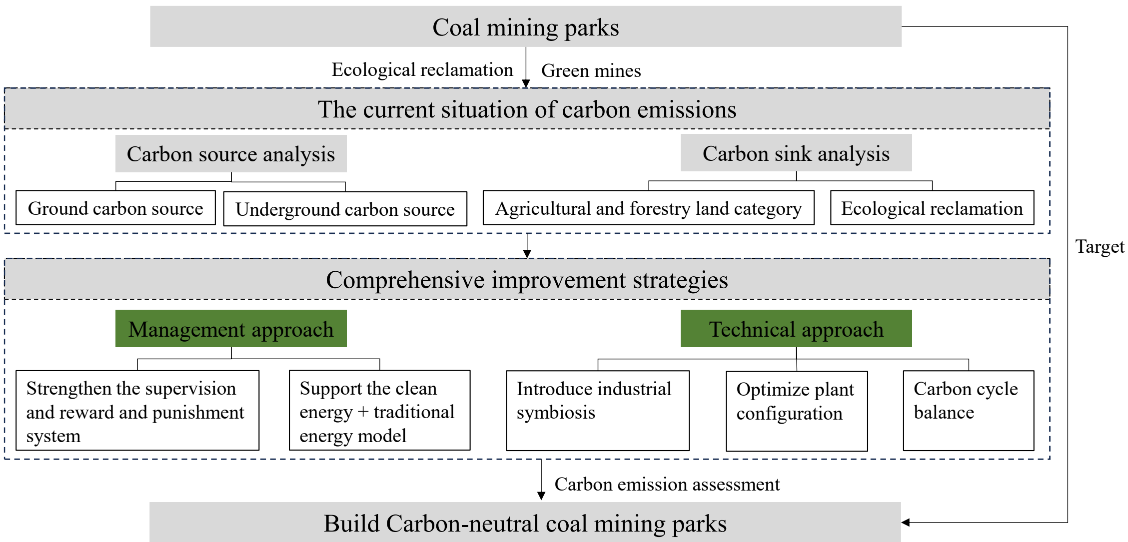

Figure 1. *Framework diagram of the carbon-neutral industrial park construction*

Comprehensive enhancement strategy

Management approaches

In terms of regional policy management, a full-process supervision and feedback system should be added. At the same time, an appropriate reward and punishment mechanism should be adopted to ensure the advancement of carbon reduction and efficiency improvement. In terms of the system, this promotes a model that combines clean energy with traditional energy through appropriate tax cuts or government procurement, which can establish and improve the carbon sink market. In terms of model, industrial symbiosis is also a very good model for carbon reduction and energy conservation. Many mining enterprises in the Yellow River Basin are facing the problem of closing their mines and transforming upon the expiration of their mining and

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excavation periods. Appropriately introducing new industries is also an important link for mining enterprises to transform and increase efficiency. At the same time, in coal mining, a large volume of waste gas, waste water, waste heat and waste materials are produced. These can be coupled with industries such as fertilizers to create an industrial symbiotic vein industrial park and reduce carbon emissions.

Technical approaches

Technically, a carbon-neutral coupled interactive system (as shown in *Fig. 2*) is constructed, which builds a circular system from the dual perspectives of carbon input and output, including two core modules: precise measurement of carbon sources and improvement of carbon sink efficiency

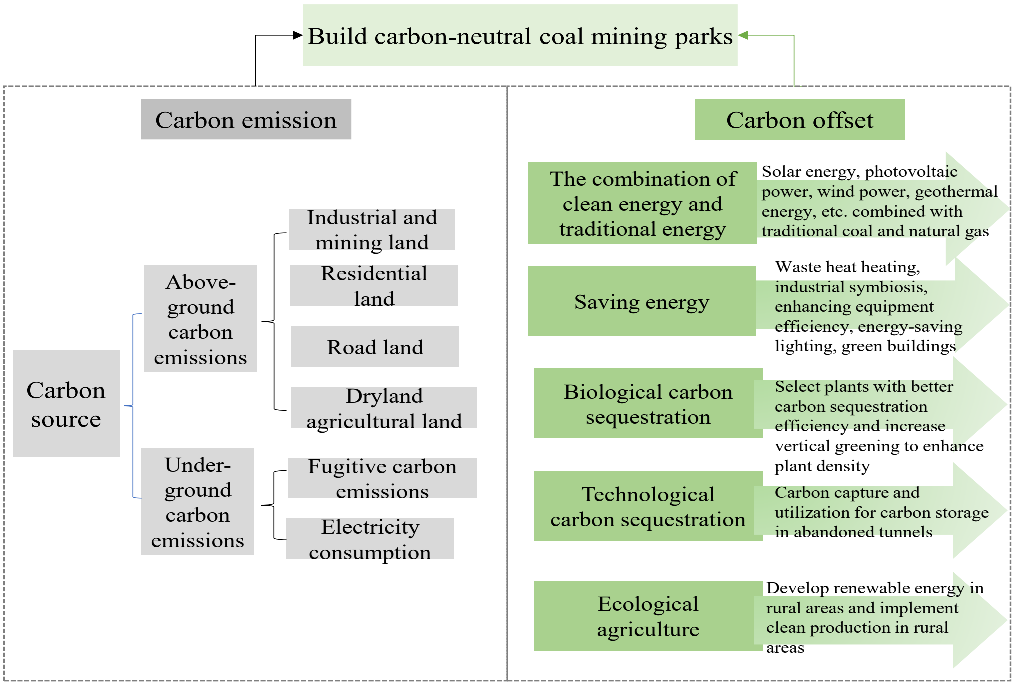

Figure 2. *Balance diagram of the carbon-neutral industrial park*

(1) Refined accounting of the carbon source module: For the ground part, due to the complexity of the land use types involved, different land uses are taken as the analysis objects, and formulas are established respectively to calculate the carbon emissions of each type of land. For the underground part, focus on the core links of coal mining and construct a carbon emission accounting model based on the mining volume.

(2) Three-dimensional accounting of carbon sink modules: At the spatial level, based on the interlaced distribution characteristics of coal industrial zones and agricultural and forestry land, integrate industrial square green spaces, coal gangue mountain reclamation areas, and agricultural and forestry land in mining fields to form a three-dimensional carbon sink network. At the ecological level, different plants, tree ages, and the configuration of trees, shrubs and grasses directly affect the carbon reserve situation. Under the premise of considering the ecological aesthetics of safe slope stabilization in accordance with local conditions, increasing carbon sink reserves is an important reference indicator for reclamation and forest land selection.

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(3) As a supplement to key technologies, carbon capture and storage (CCS) technology is introduced to build a negative carbon emission system. This technology can capture carbon dioxide throughout the entire production process (including the utilization of coal, oil and gas). After compression and transportation, it is geological stored. The effectiveness of CCS technology has been verified in the carbon reduction practice of large industrial parks (Aza et al., 2006).

Results

Carbon source accounting

In terms of carbon sources, they mainly include above-ground carbon sources and underground carbon sources. Above-ground carbon sources are primarily derived from energy consumption in industrial facilities, transportation, and processing, while underground carbon sources mainly result from the escape of coalbed methane. The industrial site of Yongning Coal Mine covers a typical underground coal industry chain, with the entire process including coal mining, transportation, processing and utilization, and each stage is accompanied by energy flow and carbon emissions. Specifically, during the mining process, rock blasting requires the use of explosives, and the operation of various large-scale machinery consumes a large volume of gasoline, diesel, and raw coal. Moreover, there is a phenomenon of coalbed methane escape after the coal seam is broken. In the links of coal transportation, processing, and power generation from gangue, the direct or indirect combustion of fossil fuels further aggravates carbon emissions. In addition, during the storage of coal and coal gangue, greenhouse gases are also released due to oxidation reactions (*Fig. 3*).

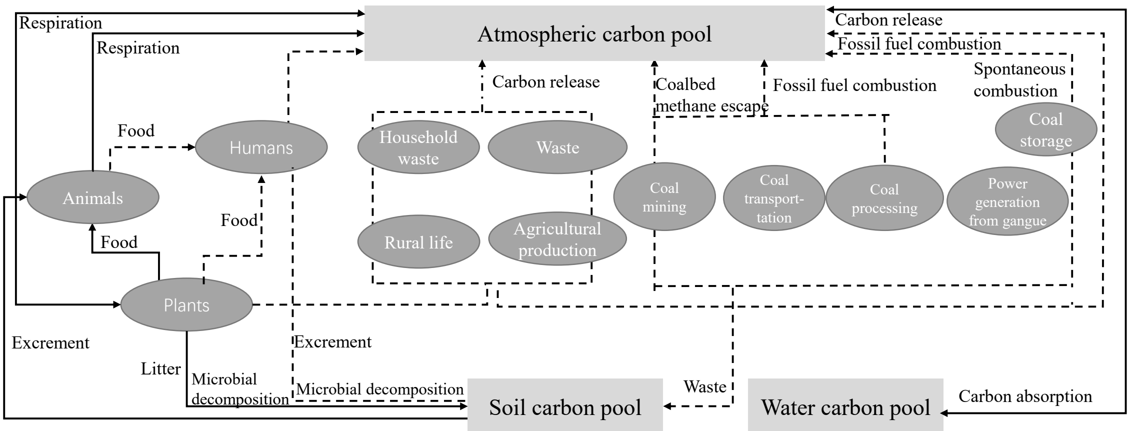

Figure 3. *Schematic diagram of the carbon cycle in the study area*

Ground carbon emission measurement and analysis

The main types of land use within the mining area of Yongning Coal Mine include industrial and mining land, residential land, shrub forest land, dryland, other grassland, and road land. Among them, the carbon emissions from industrial and mining land, residential land and road land are carbon sources. The carbon emissions of a coal mining park refer to the total volume of carbon dioxide emitted by the park within a certain period, denoted as *Pabove*. The calculation method is as follows:

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$$C_{above} = P_M + P_R + P_S + P_A \quad \text{(Eq.2)}$$

In the formula, P_M represents the carbon emissions of industrial and mining land. P_R stands for carbon emissions from residential land. P_S denotes the carbon emissions of road land. P_A means carbon emissions from agricultural land.

Carbon emissions from industrial and mining land

The area of industrial and mining land in the study zone is approximately 11.1 ha. Among them, the industrial site covers an area of 10 ha, the gangue discharge site covers an area of 0.55 ha, and the air shaft site covers an area of 0.55 ha. The types and quantities of carbon sources for industrial land in Yongning are listed in *Table 1*.

Table 1. *Types and quantities of carbon sources for industrial land in Yongning*

Types of carbon sources	Physical quantity	Folding coefficient	Equivalent quantity /t	Equivalent value /t
Electricity / 10,000 kW·h	103.8060	1.246		
Coal /t	1695.2	0.902	1529.0704	1529.0704
Diesel /t	73.46	1.4571	107.04	107.04

The carbon emissions from industrial and mining land mainly come from the electricity, coal and diesel consumed by the above-ground production system. The above-ground production system mainly includes the main inclined shaft above-ground production system (screening workshop, dynamic screening and gangue discharge workshop, product storage, and transportation), auxiliary shaft mining production system, gangue discharge system, flame retardant and fire extinguishing system, auxiliary facilities (machine repair workshop, pit wood processing room, comprehensive mining equipment warehouse, coal sample laboratory, etc.), and heating boiler room. As the gangue in the study area has been covered with soil for planting, the possibility of spontaneous combustion is extremely low, and thus its carbon emissions can be ignored (*Table 1*).

$$P_M = \sum_{m=1}^{m=n} K_m E_m \quad \text{(Eq.3)}$$

In the formula, E_m represents energy consumption. m represents the type of energy. K represents the energy carbon emission coefficient.

Carbon emissions from residential land

The carbon emissions from residential land mainly consist of energy consumption for daily life, domestic waste, and minor biological respiration (which is negligible compared to industrial sources).

Carbon emissions from road land

The carbon emissions from road land mainly come from various types of transportation vehicles. Based on the carbon emissions generated by the energy consumption E_s of transportation vehicles, it can be obtained as follows.

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$$P_s = \sum_{s=1}^{s=n} K_s E_s \times (1 - B_s) \quad \text{(Eq.4)}$$

Among them: Es represents the energy consumption of transportation vehicles; s represents the type of energy for transportation vehicles.

Carbon emissions from agricultural land

The carbon emissions from agricultural land mainly result from the consumption of agricultural production materials. There are 4.22 km^2 of dryland agricultural land in the study area.

Measurement and analysis of carbon emissions from underground coal mining

Apart from the above-ground production system, the carbon emissions from underground coal mining mainly come from the underground carbon emissions during the mining process. According to the approval document of the Shanxi Provincial Coal Industry Bureau on the identification of the mine gas grade and carbon dioxide emission volume of Yongning Coal Mine, the absolute emission volume of mine gas is approximately 647.960 t/a (taking the density of 0.00067 t/m^3 under the CH4 standard condition). Its greenhouse effect coefficient αCH4 is 21. The absolute emission of CO_2 is 2,202.916 t/a. Therefore, the total carbon emission calculation formula for underground coal mining is as follows.

$$P_{under} = Y_E = \alpha_{CH^4} Y_{ECH^4} + Y_{ECO^2} \quad \text{(Eq.5)}$$

Carbon sink accounting

Generally speaking, the carbon sinks in forest ecosystems mainly include five major Carbon sinks: aboveground biomass, underground biomass, dead wood, fallen debris, and soil organic matter. However, the area within the mining field is an ecological restoration zone, with the majority being afforestation and farmland. Forest biomass and soil account for most of the carbon storage in the forest ecosystem and are widely applied. Therefore, this paper mainly selects two major types of Carbon sinks: forest biomass (aboveground and underground biomass) and soil organic matter (Cao, 2018; Zhang et al., 2014).

The "carbon sequestration" of this project mainly come from natural carbon sequestration, including green Spaces in industrial sites, ecological forests in gangue discharge areas, forest land, agricultural land, and grassland, as shown in *Table 2*.

$$\sum C_{m\_tot} = \sum C_{wd} + \sum C_{fl} + \sum C_{bu} + \sum C_{gl} \quad \text{(Eq.6)}$$

Among them, $\sum C_{m\_tot}$, $\sum C_{wd}$, $\sum C_{fl}$, $\sum C_{bu}$, $\sum C_{gl}$ are respectively the total volume of carbon sequestration, the carbon sinks of forest land, farmland, shrub forest and grassland (including above-ground, underground parts and soil under the forest).

In the carbon sinks of forest land, industrial square green spaces, and ecological forests in gangue discharge sites, based on extensive previous studies, this paper calculates the biomass carbon storage and carbon sink capacity of trees in forest land by distinguishing different dominant tree species. The mining area is large and close to the city, so the carbon storage can roughly refer to the calculation method of the carbon storage of artificial forests. Multiply the biomass of the dominant tree species by the carbon content

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density of each tree species and the area of each tree species, and then multiply by the ratio of the molecular weight of CO2 to C. The calculation formula is as follows:

$$\sum C_{wd} = C_{wd\_i} + C_{wd_{i+1}} + \cdots + C_{wd_{i+n}} \quad \text{(Eq.7)}$$

$$C_{wd\_i} = \frac{44}{12} \times (\sum_i B_i \times S_i \times C\rho_{i_t} + S_i \times C\rho_{i_s}) \quad \text{(Eq.8)}$$

In the formula: $\sum C_{wd}$ represents the total carbon dioxide reduction of forest land. C_{wd_i} represents the carbon dioxide emission reduction of the i-th type of forest tree. $C\rho_i$ represents the carbon content rate (g/g) of the i-th tree species, $C\rho_s$ represents the carbon content rate (g/g) of the i-th tree species, and S_i represents the afforestation area (hm^2) of the *i*-th tree species at different tree age stages. B_i represents a certain type of unit biomass (t/hm^2), and the unit area reduction of the soil under the forest is 1.21 tC/hm^2 (Liu, 2016).

Table 2. *Types and characteristics of ecosystems*

NO.	Ecosystem type	Main species	Distribution	Area (hm^2)
1	Grassland ecosystem	Artemisia, carex	Distributed in the central and southern parts of the evaluation area	250.75
2	Agricultural ecosystem	Corn, millet, beans, wheat, etc.	Distributed in patches or bands throughout the evaluation area	302.29
3	Forest land ecosystem (dominated by trees)	Larch and oil pine from North China, spruce, sea buckthorn, yellow rose, caragana, hazelnut, jujube, and Chinese jujube, etc.	Distributed in patches in the northern, middle and southern parts of the mining field, and in strips	81.49 (Among them, shrub forest account for approximately 28.52)
4	Industrial Square Green Space	Locust trees and poplar trees	Inside the Industrial Square	2.1
5	Ecological restoration of the gangue discharge site	Poplar trees	A desolate ditch 330 meters northeast of the Industrial Square	0.23

Data source: Environmental Impact Assessment Report of Yongning Coal Mine

Then, through the biomass estimation formula:

$$B_i = a + bV_i \quad \text{(Eq.9)}$$

Among them, V_i represents a certain type of unit volume (m^3/hm^2), a and b are constants, and i represents a certain type (i = 1,2,3,... n).

The carbon sink parameters of forest land can be obtained by referring to the carbon storage and carbon density calculated based on the statistics table of dominant tree species of tree forests in all provinces, autonomous regions and municipalities across the country in the “Research on Dynamic Changes of Forest Vegetation Carbon Storage”. The parameters for dominant tree species can be obtained nationwide. The parameters for dominant tree species are selected by referring to the research literature in Shanxi region (Wang, 2014, 2009; Fang et al., 1996; Yu et al., 2008; Liu et al., 2019; Li et al., 2013), as shown in *Table 3*.

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Table 3. *Statistics of unit volume and correlation coefficient of dominant tree species in Yongning coal mining park*

Dominant tree species types	**Unit volume $V_i/(m^3/hm^2)$**	**Coefficient**		
		Carbon content rate $C\rho_{ij}$	**a**	**b**
Locust tree plantation	23.14	0.4649	8.3103	0.7564
Poplar plantation	46.25	0.4701	30.6034	0.4754
Oil pine plantations	73.5	0.465	5.0928	0.7554
Spruce plantation	193.47	0.4889	47.4999	0.4642

In the industrial square green space and ecological restoration area of Pai Gangue Mountain, the parameters of the artificially planted young trees are based on the studies of Yu et al. (2008; Zhu, 2020), as shown in *Table 4*.

Table 4. *Statistics on the unit volume and correlation coefficient of dominant tree species (young) in Yongning Coal Mining Park*

Dominant tree species types	**a**	**b**	**Carbon content rate $C\rho_{ij}$**
Poplar tree	21.56	0.575	0.4701
Oil pine	14.4807	0.7106;	0.465
Deciduous broad-leaved leaves	21.8281	0.7084	0.4722

As it is difficult to count the quantities of shrubs, crops and herbaceous plants, this paper adopts the method of multiplying the unit area emission reduction coefficient by the area to estimate the carbon dioxide reduction of farmland, grassland, and shrubs (see *Eqs. 5–7*). The farmland ecosystem, shrub forest and grassland ecosystem mainly refer to the studies of Liu et al. (2016; Fang et al., 2020).

$$\sum C_{fl} = S_{fl} \times C\rho_{fl} \quad \text{(Eq.10)}$$

$$\sum C_{bu} = S_{bu} \times C\rho_{bu} \quad \text{(Eq.11)}$$

$$\sum C_{gl} = S_{gl} \times C\rho_{gl} \quad \text{(Eq.12)}$$

S_{fl}, S_{bu}, and S_{gl} represent the areas of farmland ecosystem, shrub forest, and grassland respectively. $C\rho_{fl}$ represents the emission reduction per unit area of agricultural land for growing corn, millet, and legumes in Shanxi Province, which is 4.34 tC/hm^2 (including 3.28 tC/hm^2 for plants and 1.02 tC/hm^2 for soil). The reduction per unit area of shrubs in $C\rho_{bu}$ was 37.47 tC/hm^2 (including 36.26 tC/hm^2 reduction by plants and 1.21 tC/hm^2 reduction by soil). $C\rho_{gl}$ represents a carbon reduction of 7.09 tC/hm^2 per unit area of grassland (the carbon density of the aboveground part is 0.89 tC/hm^2, and that of the underground part is 6.23 tC/hm^2).

According to the area of various land uses provided in the "Environmental Impact Assessment Report of Yongning Coal Mine", the "carbon sequestration" of this project are approximately 13,060.70 tons per year (t/a).

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To sum up, based on the current limited data calculation results, the carbon emissions are far greater than the carbon sink capacity. Therefore, exploring how to achieve carbon-neutral transition mining areas is of great significance.

Discussion

In the process of achieving the goal of carbon-neutral coal mines, two different situations may arise. The first one is the carbon offset model, where carbon reduction measures (clean energy supply, energy conservation, and carbon sequestration) cannot balance the carbon emissions and carbon reduction of industrial parks. However, given the low cost-effectiveness of purchasing carbon credits and the physical limits of offsets, this approach is treated as a last resort. The second scenario is inherent carbon balance: when implemented measures achieve net-zero carbon emissions through internal carbon sequestration, eliminating the need to purchase carbon emission permits. Excess carbon sequestration capacity can be monetized.

(1) Combination of multiple clean energy sources with traditional ones: As coal enterprises produce coal themselves, they generally use traditional energy sources such as coal for power generation. Luliang City enjoys abundant sunshine and highly developed wind power. It should fully leverage its own advantages, implement China's Renewable Energy Law and Energy Conservation Law, and adopt a combined model of photovoltaic power generation, wind power generation, geothermal energy, and traditional energy in production land. Rural residential areas can fully recycle and utilize agricultural waste, vigorously promote the combination of renewable energy such as biogas and solar energy, and pay attention to the recycling of biomass energy to ensure the energy supply for daily life in rural residential areas within the mining field. The mine-village collaboration should gradually implement the clean reform of the energy structure.

(2) Energy conservation model: In China's climate zones, Luliang belongs to the cold climate zone. Coal enterprises work for long hours, and the time for lighting and heating is also long, resulting in a large consumption of energy. Energy conservation is a very important measure for carbon reduction. Therefore, effectively controlling electricity and heating consumption can effectively alleviate carbon emissions. a. Recycle energy. For instance, the waste heat from coal production is used for district heating. b. Introduce new high-efficiency equipment and increase operation and maintenance. c. LED or infrared sensing lighting methods used to reduce power consumption for lighting. d. It is suggested that energy-saving renovations be carried out on buildings within the area, and energy-saving requirements be put forward for new building materials, structures, etc.

(3) Biological carbon sequestration model: Generally speaking, the carbon sink capacity of plants is related to the carbon density, area, and conversion rate of dominant species. However, it is crucial to acknowledge that carbon sequestration capacity is finite and subject to saturation over time. Therefore, in the creation of green spaces, the selection and breeding of artificial forests, and the selection of replanting, plant combinations with strong carbon sink capacity should be given priority under the premise of considering adaptability and aesthetic requirements. In the Luliang area, coniferous trees, spruce, fir, cedar, poplar, locust, ginkgo and other tree species with strong carbon sink capacity can be given priority. Carbon sinks can also be increased by multi-layer mixed intercropping by raising the canopy density to around 0.6 (Cao, 2018), or by appropriately adding vertical ground greening such as roof gardens, or by vertical farming systems for soilless planting of low-light and water-tolerant plants in above-ground

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facilities. In farmland cultivation, the current traditional agricultural production methods that extensively use pesticides, chemical fertilizers, and plastic mulch should be controlled and improved. The proportion of ecological agriculture and organic agriculture should be increased to protect the environment while comprehensively enhancing the carbon sequestration level of crops.

(4) Technical carbon sequestration model: Substances such as amines capture carbon dioxide from industrial point sources (e.g., coal processing facilities), followed by geological storage in underground goaf areas or abandoned tunnels. This carbon capture and storage (CCS) technology provides a critical pathway to achieve carbon neutrality for coal mining parks by offsetting residual emissions.

Conclusion

As a pillar industry for high-quality economic development in the Yellow River Basin, the coal industry is highly necessary to undergo a carbon-neutral transformation in the new era of green and carbon-neutral development. Although the current mine-zone collaborative coal mining parks attach great importance to environmental protection, there is still room for improvement in carbon sequestration and reduction. Two approaches, carbon offsetting and inherent carbon balance, can be considered. While carbon offsetting provides short-term flexibility, its long-term economic viability is limited by rising permit prices and saturation of offset projects. Considering long-term benefits, achieving carbon neutrality in industrial parks through the integration of various clean and traditional energy sources, energy conservation, biological carbon sequestration, and carbon capture and storage (CCS) represents a promising path for the sustainable development of high-carbon industries, such as coal mining industrial parks in China.

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