



Research on Carbon Emissions and Low Carbon Transformation Path in Huainan City Based on LEAP Model



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Abstract

To explore the low-carbon transformation path of resource-based cities, this paper takes Huainan City as the research object and builds an energy-carbon emission accounting framework based on the LEAP model. This framework divides the terminal energy consumption into six sectors: residents, agriculture, buildings, industry, transportation, and services. The energy conversion system is subdivided into two modules: power generation and heat production. It innovatively incorporates the carbon capture, utilization and storage (CCUS) technology path. Based on this, it simulates the energy demand and carbon emission trends under three scenarios: the baseline, development, and enhanced low-carbon scenarios from 2022 to 2050. The results show that the carbon emissions in the baseline scenario peak in 2035 at 89.625 million tons of CO₂ equivalent, which is difficult to meet the "dual carbon" goals. In the development scenario, carbon emissions peak in 2031 at 76.548 million tons of CO₂ equivalent, and carbon neutrality is still difficult to achieve by 2050. In the enhanced low-carbon scenario, carbon emissions peak in 2029 at 68.923 million tons of CO₂ equivalent, and the carbon emissions in 2050 are 58.3% lower than those in the baseline scenario. Through the contribution rate analysis of emission reduction measures using the LEAP model, it is found that the clean-up of the power sector, the electrification of the terminal, and energy efficiency improvement are the main driving forces for emission reduction, with contribution rates of 42.6%, 23.5%, and 21.8% respectively. The industrial and transportation

sectors are the key areas for emission reduction. This study can provide scientific support for the formulation of the "dual carbon" goals in Huainan City and also offer a reference for the low-carbon transformation of similar resource-based cities.

Keywords: LEAP model; energy demand; carbon emissions; contribution analysis; low-carbon development

1 Introduction

While fossil fuels have driven the progress of human civilization, the greenhouse gases and pollutants generated from their combustion have intensified global warming and caused irreversible environmental damage. Given China's energy endowment characterized by "abundant coal but scarce oil," the Chinese Academy of Sciences has coordinated national energy security and ecological protection [1], and proposed the goals of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060 [2], demonstrating China's strong commitment to addressing climate change. After long-term governance efforts, China's carbon emission intensity has declined by more than 50% compared with that in 2000, making a significant contribution to global climate governance [3–6]. As cities are the core carriers of carbon emissions, their low-carbon transition is crucial for implementing the "dual-carbon" strategy. However, existing studies have mainly focused on the national and provincial levels, while systematic low-carbon research at the city level in Anhui Province remains insufficient. In particular, the carbon emission characteristics and mitigation potential of Anhui cities, as an emerging growth pole in the Yangtze River Delta, have not been adequately revealed [7–9]. This gap constrains the formulation of region-specific differentiated strategies and highlights the need for deeper analysis at the urban scale.

Economic–environment–energy system models can generally be classified into three categories [10]. The first is top-down models (such as CGE and STIRPAT), which are based on macroeconomic analysis but are limited in reflecting technological impacts. The second is bottom-up models (such as MARKAL and LEAP), which focus on the technological level and can effectively analyze the

roles of policies and technologies [11]. The third is integrated models, which combine the advantages of both approaches, but their applications are restricted by high modeling complexity and extensive data requirements. As a bottom-up tool, the LEAP model predicts energy demand, carbon emissions, and associated benefits through scenario construction. Owing to its flexible modeling framework and wide applicability across sectors, it has been extensively used in low-carbon strategy formulation [12]. For example, Xing Xiaowen et al. found that China's coal consumption and carbon emission peaks could be advanced without suppressing economic growth [13], while Chen Yuguang projected the carbon emission trends of Zhejiang's energy consumption under eight scenarios [14].

Huainan, as a typical coal resource-based city [15–20], achieved an average annual GDP growth rate of 6.5% from 2016 to 2022, with GDP reaching CNY 154.107 billion in 2022 and total energy consumption amounting to 10.6205 million tons of standard coal. Its energy structure has long been dominated by coal and electricity, and the carbon emission intensity of fossil energy is higher than the provincial average, resulting in considerable pressure for emission reduction. Based on the energy–carbon accounting framework constructed with the LEAP model, this study, for the first time, incorporates the electricity balance logic of “local power generation = local final electricity consumption + exported electricity” into the model in view of the characteristics of coal resource-based cities. This approach enables more accurate accounting of carbon emissions from the production processes corresponding to exported electricity, thereby addressing the bias in traditional models when estimating carbon emissions in “coal-fired power exporting” cities. For Huainan, this accounting framework makes it possible to precisely identify the carbon emission contribution of “coal-fired power export,” its core industry, thus providing data support for optimizing the scale of electricity export and the pace of cleaner retrofitting. For similar coal resource-based cities such as Datong and Yangquan, which also exhibit characteristics of power export, this accounting logic can be directly adopted to avoid biases in mitigation strategies caused by neglecting the carbon emissions embodied in exported electricity.

To promote the green transformation of resource-based cities and support Anhui Province in achieving its “dual-carbon” targets, this study employs the LEAP model to simulate the dynamic

carbon emissions of Huainan from 2022 to 2050, and to analyze its energy consumption characteristics and emission reduction pathways. By comparing different scenarios, the mitigation effects are evaluated and a quantitative analytical framework is established, providing support for the formulation of Huainan's "dual-carbon" strategy and offering a reference for other similar cities [21–23].

2 Methods

2.1 LEAP Model Construction

Based on the survey data, greenhouse gas emissions generated by energy activities account for 82.17% of the city's total emissions, while the contribution of other sectors is relatively limited. Among them, carbon emissions from energy activities account for 89.18% of total carbon emissions, constituting the dominant source of emissions. Therefore, this study focuses on carbon accounting in the energy activity sector. For the industrial sector, only direct combustion emissions are included, whereas emissions from industrial processes and fossil fuels used as raw materials are not considered at this stage.

This study constructs an energy–carbon accounting structure for Huainan based on the LEAP model. The model strictly follows the accounting standards of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and adopts a sectoral approach in which final energy consumption is divided into six major sectors: residential, agriculture, construction, industry, transport, and services. The energy transformation system is further subdivided into two modules: power generation and heat production. The power generation system mainly simulates Huainan's coal-dominated energy structure [24], while also considering renewable generation technologies such as wind power and photovoltaics. In addition, this study innovatively incorporates the technological pathway of carbon capture, utilization, and storage (CCUS). Combined with the "coal–power–chemical" industrial linkage characteristic of coal resource-based cities, the study further integrates CCUS with the control of fossil fuel combustion emissions in industrial sectors such as the chemical and steel industries, thereby forming a coordinated technical analysis framework of "coal-fired power +

industry” decarbonization. This framework overcomes the limitation of traditional LEAP applications that focus only on single-sector technologies. For Huainan, this coordinated decarbonization framework can support the formulation of combined strategies such as “CCUS retrofitting of coal-fired power plants + low-carbon feedstock substitution in the chemical industry.” For example, the CO₂ captured from coal-fired power generation can be used in chemical parks for methanol synthesis, thereby realizing resource recycling. For similar coal resource-based cities such as Xuzhou and Huaibei, which also have “coal–power–chemical” industrial chains, this technical combination can provide a useful reference, helping avoid the excessive overall mitigation costs caused by single-sector decarbonization and improving decarbonization efficiency across the entire industrial chain.

A sector-based accounting approach is adopted in this study, under which final energy demand is divided into two sources: locally produced supply and externally imported supply. Electricity demand is assumed to be supplied only by local power generation, and local power generation is further divided into local final electricity consumption and electricity exported to other regions. Heat demand is assumed to be fully supplied by local production. The energy transformation sector is responsible for converting primary energy into local electricity and heat, and all emissions generated during the electricity production process are accounted for in the energy transformation sector [25]. To avoid double counting, the final demand sectors only include the electricity actually consumed locally, whereas the carbon emissions corresponding to exported electricity have already been included in the accounting of the energy transformation sector.

The total final energy demand of the region can be calculated as follows:

$$ED = \sum EC_k + \sum ET_k$$

where ED denotes the total regional energy demand (tce, tons of standard coal); EC_k denotes the demand for the *k*-th type of energy in the final energy consumption sectors (tce); ET_k denotes the input of the *k*-th type of energy in the energy transformation sector (tce), including all energy inputs for local power generation, corresponding to the relationship of “local power generation = local final electricity consumption + exported electricity”; and EP denotes imported electricity (tce).

In this study, the final demand sectors are divided into six categories: residential, agriculture, construction, transport, industry, and services ($m = 1, 2, 3...6$), among which the industrial and transport sectors are identified as the key emission sectors. The energy demand of each final demand sector is calculated using the following method:

$$EC_k = \sum AL_{m,n} \times EI_{m,n} \times S_{m,n,k}$$

where $AL_{m,n}$ represents the activity level of the n -th subsector in sector m ; $EI_{m,n}$ represents the energy intensity per unit activity of that subsector; and $S_{m,n,k}$ represents the share of the k -th type of energy in final energy consumption, including electricity, coal, oil, and other energy sources.

By combining the results of final energy demand with the carbon emission factors of different energy types, the carbon emissions of the final demand sectors can be calculated as follows:

$$CE = \sum k EC_k \times EF_k$$

where CE denotes carbon emissions (tCO₂-eq), and EF_k denotes the carbon emission factor of the k -th type of energy (tCO₂/tce).

2.2 Data Sources

Accurate and reliable carbon emission forecasting depends on the rationality of the underlying data. In this study, multi-source data were adopted to ensure the accuracy of the estimation. Activity level data, including GDP, permanent resident population, urbanization rate, and industrial output, were obtained from the official statistical materials published by the Huainan Municipal Bureau of Statistics. Sectoral energy consumption data were derived from survey data collected by the local statistical authorities. In particular, electricity data were carefully distinguished between local final electricity consumption and exported electricity, and the energy inputs for power generation in the energy transformation sector were calibrated according to the relationship “local power generation = local final electricity consumption + exported electricity”, so as to ensure that the production-side energy consumption corresponding to exported electricity was fully included [26–29].

With regard to emission factors, the net calorific value and carbon emission coefficient of coal were determined using weighted averages based on enterprise survey data, while the calorific values of other fuels were taken from the default parameters in the environmental technology database of the LEAP model. Carbon emission coefficients strictly followed the standards set forth in the 2006 IPCC Guidelines. The electricity emission factor was based on the average CO₂ emission factor of the Anhui power grid in 2016, namely 0.7759 kg/kWh, which was converted into consistent units before use. The key parameters of all scenarios were determined on the basis of policy planning documents of Huainan City and authoritative research literature.

2.3 Scenario Setting

Based on the LEAP model, this empirical study established a multi-scenario analytical framework for carbon emissions in Huainan. The results indicate that regional carbon emissions are jointly influenced by multiple factors, including the rate of economic growth, the degree of industrial structure optimization, the proportion of clean energy substitution, and the extent of improvement in end-use energy efficiency. According to the Implementation Plan for Energy Conservation and Emission Reduction during the 14th Five-Year Plan Period of Huainan City, coal-fired power generation accounted for 79.6% of total power generation in 2020, and its generation efficiency played a decisive role in determining carbon emissions from the power sector.

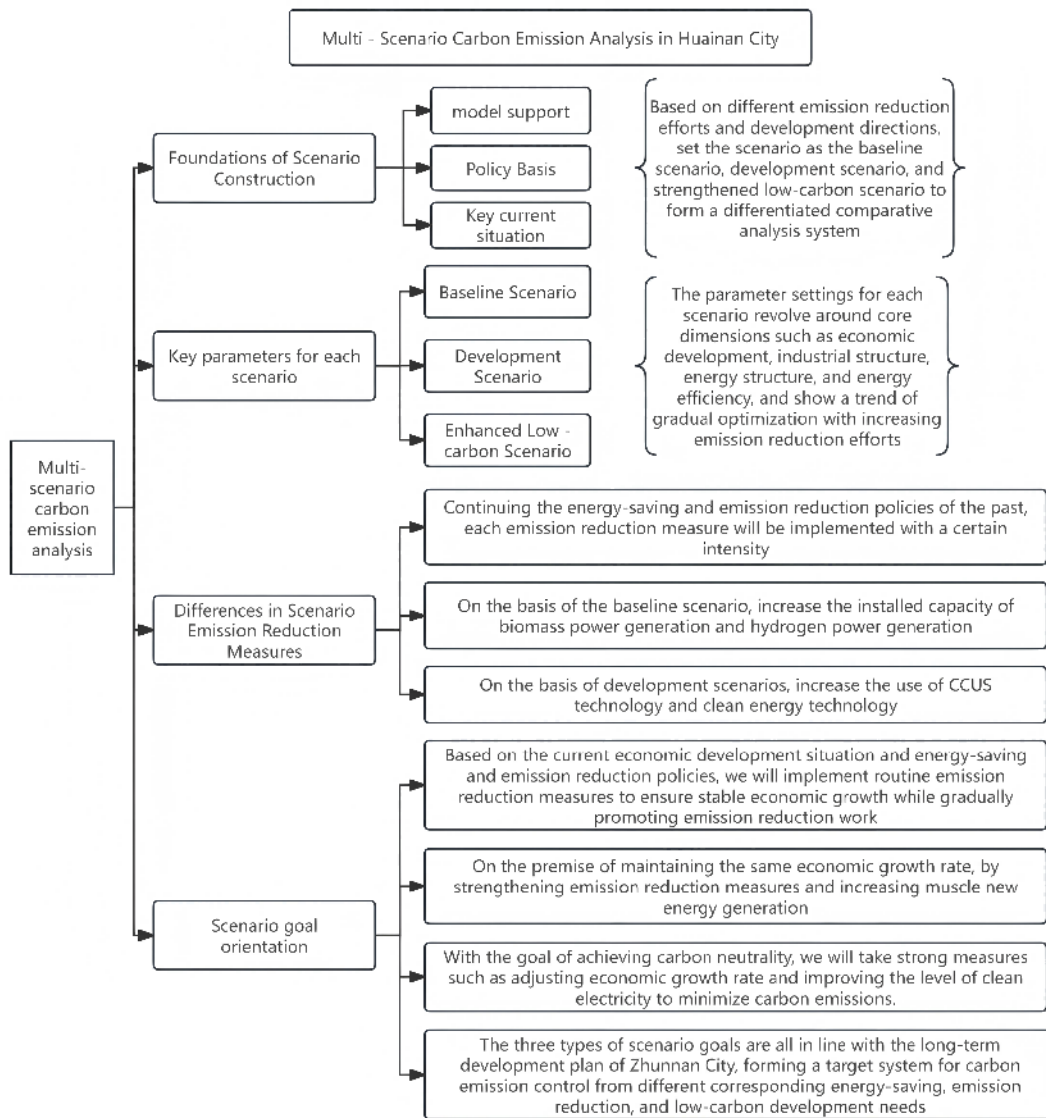


Fig 1 LEAP-Huainan City Prediction Model Framework

In this study, three differentiated scenarios were designed on the basis of varying mitigation intensities and development orientations, with reference to the 14th Five-Year Plan of Huainan City and the Outline of the Long-Range Objectives through 2035. The core parameters were adjusted in a gradient manner across dimensions such as economic growth rate, industrial structure, energy structure, and energy efficiency improvement (specific parameter settings are presented in Table 1).

The baseline scenario follows the inertia of current energy-saving and emission-reduction policies and advances mitigation at the existing pace of development. The development scenario builds on

the baseline scenario by strengthening measures for clean energy substitution and energy efficiency improvement. The enhanced low-carbon scenario, aiming toward carbon neutrality, further increases the deployment of renewable energy, introduces CCUS technology, and optimizes the economic growth rate, thereby implementing a more intensive emission reduction strategy.

Table1 Comparison of key parameters under different scenarios in Huainan City

Scenario type	Baseline Scenario	Development Scenario	Enhanced carbon Scenario	Low-
Annual GDP growth rate (%)	6.5	5.5	5.5	
Proportion of the tertiary industry in 2050 (%)	55	60	65	
Proportion of coal-fired power generation in 2050 (%)	65	50	30	
Proportion of renewable energy generation in 2050 (%)		35	55	
CCUS Technology Application Status (%)			30	
Annual average increase in terminal electrification rate (%)	0.5	0.8	1.2	
Annual average decrease in energy consumption intensity of each department (%)	1.2	1.8	2.5	

3 Results and Analysis

3.1 Forecast Analysis of Energy Demand

Figure 2 serves as a visual presentation of Huainan’s core environment-related data in 2022. It systematically covers 13 key indicators, including municipal solid waste treatment, domestic sewage treatment, industrial wastewater treatment, medical waste disposal, and total greenhouse gas emissions. The figure not only intuitively reflects the scale differences among the city’s annual environmental indicators, but also closely corresponds to the analysis of energy demand, carbon

emission accounting, and low-carbon transition in this study, thereby providing benchmark data support for subsequent scenario simulation and pathway analysis.

From the perspective of data magnitude, the high-value indicators highlight the major sources of environmental pressure. In particular, emissions from fossil fuel combustion (204.7571 million tons) and total greenhouse gas emissions (204.0685 million tons) are very close in value and significantly higher than the other indicators. This result directly confirms the key conclusion presented in Section 2.1, namely that greenhouse gas emissions from energy activities account for 82.17% of the city's total emissions, while carbon emissions account for 89.18%, clearly indicating that fossil fuel combustion is the primary driver of greenhouse gas emissions in Huainan. This also explains why the present study focuses on the energy activity sector as the core area of carbon emission accounting. Furthermore, when considered together with the background information that Huainan consumed 10.6205 million tons of standard coal in 2022 and has long maintained an energy structure dominated by coal and electricity, the high-emission data reflect the city's long-standing dependence on fossil fuels as a coal resource-based city. This industrial and energy structure provides a practical basis for the mitigation measures proposed in subsequent scenarios, such as power sector decarbonization and end-use electrification.

The medium-scale indicators reflect the coordinated relationship among multiple areas of environmental governance. For example, the data on straw utilization (4.1032 million tons) indicate the effectiveness of resource recycling in Huainan's agricultural sector. This finding is conceptually consistent with the low-carbon pathway proposed in Section 4.1 for the industrial sector, which emphasizes the construction of a circular economy system, suggesting that agriculture and industry may achieve cross-sectoral synergy in terms of efficient resource utilization. In addition, the indicator of emissions from various sectors (81.0446 million tons), representing the aggregated emissions of multiple fields, contrasts with the higher value of fossil fuel combustion emissions. This demonstrates that, although emissions from sectors such as industrial production processes and agricultural activities account for a relatively smaller share than energy-related emissions, they remain important components of the overall low-carbon transition. This is also consistent with the

analytical logic in Section 3.2, which emphasizes that the power and industrial sectors are the principal emission sources, while coordinated mitigation across multiple sectors is also necessary.

Although the low-value indicators are relatively small in magnitude, they also represent critical points for targeted management and control. Indicators such as industrial wastewater treatment (0.92 million tons) and medical waste disposal (0.78 million tons) fall into this category. Taking industrial wastewater treatment as an example, the data correspond to the COD generation and discharge associated with representative industrial enterprises, indicating that pollution control in key industrial firms has already achieved initial results. However, in light of the requirement in Section 4.1 that the industrial sector should promote the green upgrading of high-energy-consuming industries, such indicators should still serve as important references for refined management and control in the process of industrial low-carbon transition. Similarly, the data on medical waste disposal reflect the basic status of hazardous waste management in Huainan and provide foundational support for the subsequent improvement of the environmental safety control system.

Overall, through a stratified presentation of the data, the figure clearly reveals both the principal challenge and the secondary tasks of environmental governance in Huainan in 2022. On the one hand, the high carbon emissions dominated by fossil fuel combustion constitute the core challenge to achieving the dual-carbon goals, which requires high-intensity measures such as cleaner power generation and energy efficiency improvement. On the other hand, efforts such as the resource utilization of agricultural straw and refined management in industrial and medical sectors serve as important complements to the construction of a comprehensive low-carbon governance system. These data not only provide a realistic basis for parameter setting in the baseline scenario of the LEAP model, but also verify, from a practical perspective, the necessity of coordinated multi-measure emission reduction under the enhanced low-carbon scenario. Therefore, they offer data-based and visualized decision support for formulating sector-specific low-carbon development pathways in Huainan.

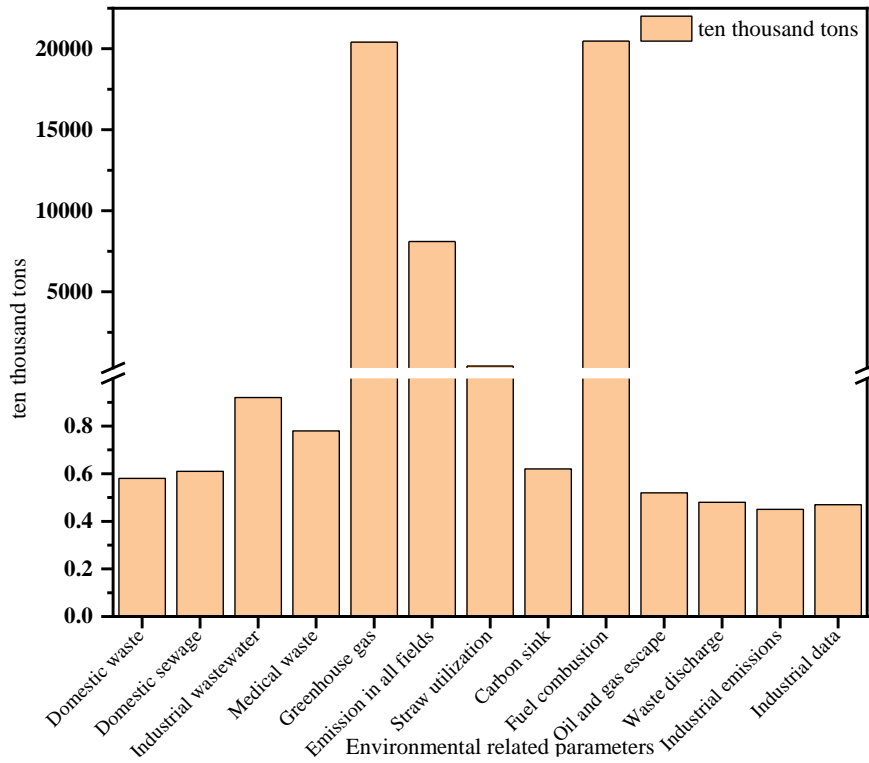


Fig 2 Summary Table of Environmental Related Data in Huainan City in 2022

3.2 Forecast Analysis of Carbon Emissions

The simulated carbon emission trends of Huainan from 2022 to 2050 under the three scenarios are shown in Figure 3. Under the baseline scenario, carbon emissions continue to increase and reach a peak of 89.625 million tCO₂-eq in 2035, followed by a slow decline. By 2050, carbon emissions remain at 78.352 million tCO₂-eq, representing an increase of 23.6% compared with the 2022 level. Under this scenario, the carbon peak occurs later than the national target of 2030, and the peak value remains relatively high, making it difficult to meet the requirements of the dual-carbon strategy.

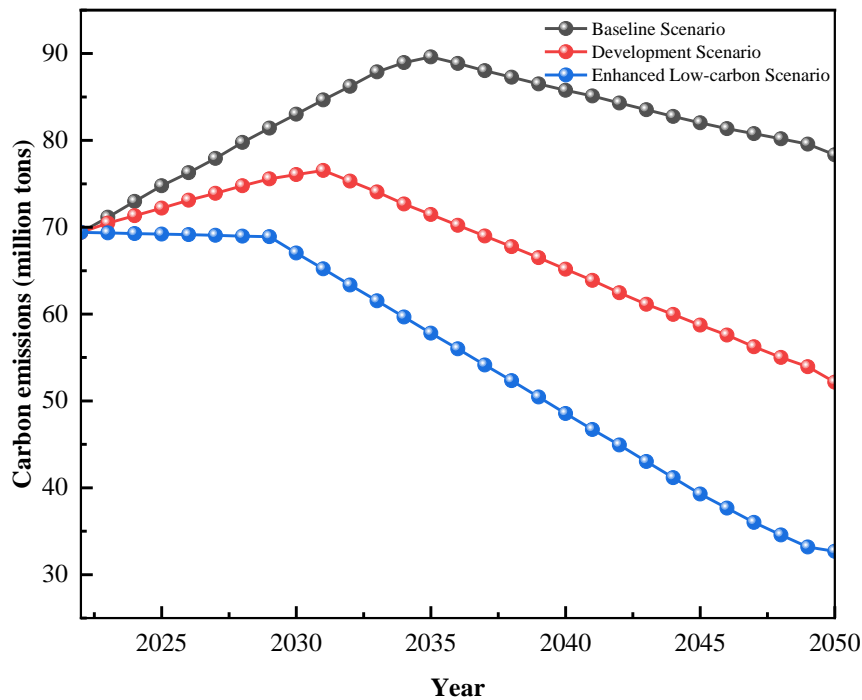


Fig 3 Carbon emission prediction and simulation of various departments in Huainan City

Under the development scenario, carbon emissions peak in 2031 at 76.548 million tCO₂-eq, and decline to 52.163 million tCO₂-eq by 2050, representing a 33.4% reduction compared with the baseline scenario in the same year. Through enhanced clean energy substitution and energy efficiency improvement, this scenario achieves an earlier carbon peak. However, due to the still limited mitigation intensity, carbon emissions remain at a relatively high level in 2050, leaving a considerable gap from the carbon neutrality target.

Under the enhanced low-carbon scenario, carbon emissions show a rapid downward trend, peaking in 2029 at 68.923 million tCO₂-eq, and decreasing to 32.685 million tCO₂-eq by 2050, which is 58.3% lower than that under the baseline scenario and 37.3% lower than that under the development scenario. Under this scenario, the implementation of comprehensive and high-intensity mitigation measures not only enables an earlier carbon peak, but also lays a solid foundation for achieving the 2060 carbon neutrality target [30–32].

3.3 Analysis of the Contribution Rates of Emission Reduction Measures

The calculated contribution rates of various emission reduction measures under the enhanced low-carbon scenario in 2050 are shown in Figure 4. Among all measures, power sector decarbonization makes the greatest contribution, with an emission reduction of 18.652 million tCO₂-eq and a contribution rate of 42.6%. This is mainly attributable to the large-scale deployment of renewable energy generation, such as wind power and photovoltaics, as well as the application of CCUS technology in coal-fired power units, which significantly reduce the carbon emission intensity of the power sector.

Based on the contribution rate analysis, this study proposes, for the first time, a priority matrix of emission reduction measures for coal resource-based cities. The matrix classifies mitigation measures into core priorities (*power sector decarbonization* and *end-use electrification*), important priorities (*energy efficiency improvement*), and supporting priorities (*industrial structure adjustment* and *optimization of economic growth*). It also specifies the applicable stages for different categories of measures; for example, core-priority measures should be promoted during 2025–2035, while supporting-priority measures should be further integrated after 2035.

For Huainan, this matrix can guide the phased allocation of mitigation resources. For instance, during 2025–2035, priority can be given to investment in wind and photovoltaic power stations and transport electrification, thereby avoiding the dispersion of limited resources. For similar coal resource-based cities such as Jixi and Shuangyashan, which also face constraints in mitigation funding, this priority matrix can help accurately identify the most critical emission reduction directions and improve the effectiveness of limited resources.

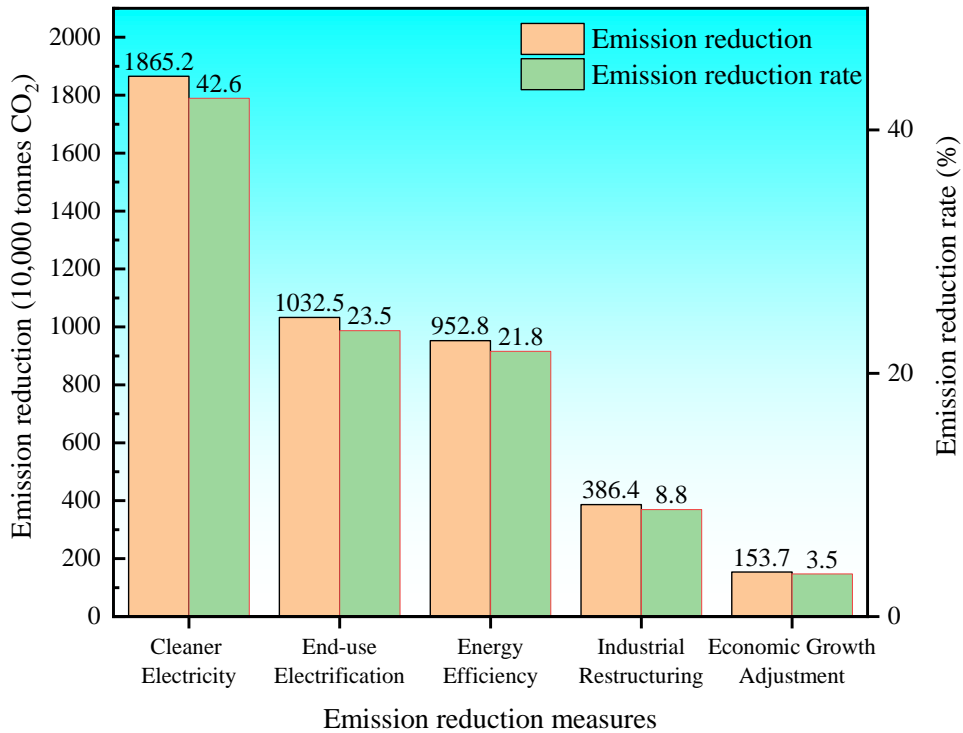


Fig 4 Prediction of emission reduction contribution of various emission reduction measures in Huainan city under the enhanced low-carbon scenario in 2050

The accelerated end-use electrification measure ranks second, with an emission reduction of 10.325 million tCO₂-eq and a contribution rate of 23.5%. Among these, the widespread adoption of electric vehicles in the transport sector and the application of electric heating technologies in the industrial sector constitute the main sources of contribution, effectively substituting for conventional consumption of petroleum fuels and coal.

The energy efficiency improvement measure contributes an emission reduction of 9.528 million tCO₂-eq, accounting for 21.8% of the total. Through technological upgrading and management optimization across sectors, energy consumption per unit of output declines substantially, with particularly significant results achieved through energy-saving retrofits in the industrial sector.

The industrial structure adjustment measure contributes an emission reduction of 3.864 million tCO₂-eq, with a contribution rate of 8.8%. This reduction is mainly realized by increasing the share of the tertiary sector and reducing the proportion of energy-intensive industries.

The economic growth rate adjustment measure contributes an emission reduction of 1.537 million tCO₂-eq, accounting for 3.5% of the total. A moderate reduction in the economic growth rate helps curb the incremental carbon emissions associated with rising energy demand.

3.4 Trend Analysis of Energy Demand in the Industrial, Transport, and Service Sectors

As shown in Figure 5-1, energy demand in the industrial sector exhibits a continuous downward trend from 2020 to 2050. Starting from 3.4625 million tce in 2020, it gradually declines to 1.502 million tce by 2050 after three decades of development. This change reflects the effective implementation of a series of measures under the enhanced low-carbon scenario. With the continuous improvement of energy efficiency in the industrial sector, various energy-saving technologies are widely applied, substantially reducing energy waste in the production process. At the same time, the rising electrification rate enables more industrial processes to reduce their dependence on traditional fossil fuels, while the share of coal in energy consumption continues to decline. These transformations clearly reflect the overall trend of continuously optimized and reduced energy demand in the course of the industrial sector's green transition.

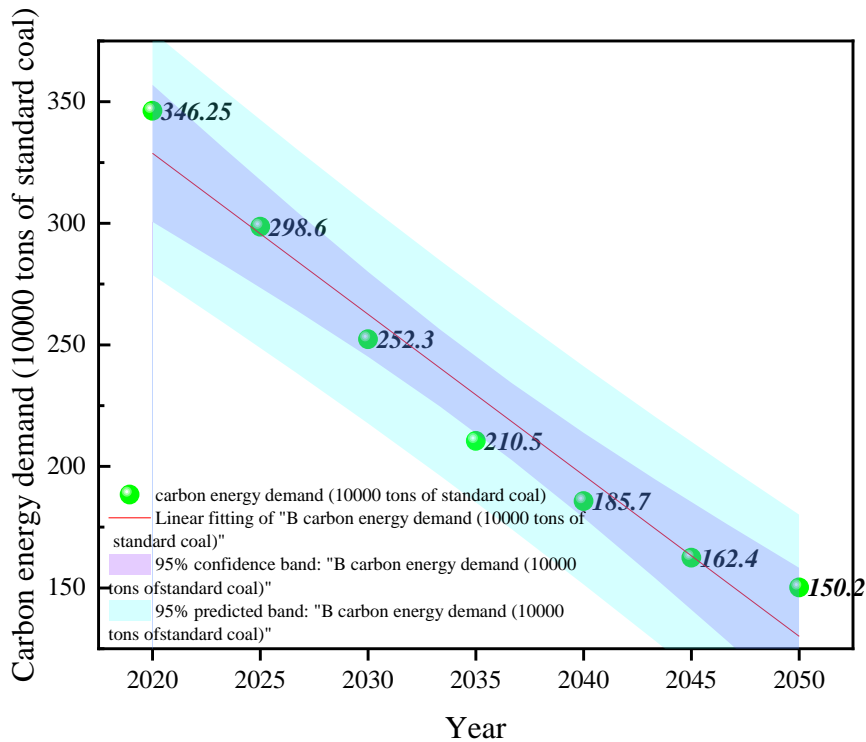


Fig 5-1 Summary of Energy Demand in the Industrial Sector

As shown in Figure 5-2, the trend of energy demand in the transport sector differs somewhat, exhibiting a pattern of initial increase followed by gradual decline. Energy demand in the transport sector was 2.282 million tce in 2020, then increased for a certain period before gradually decreasing to 0.603 million tce by 2050. This trend is closely associated with the process of transport electrification.

In the initial stage, although new energy vehicles began to be promoted, conventional fuel vehicles still accounted for a considerable share of transport activity. Coupled with the growing demand for mobility, this led to a temporary increase in overall energy demand. However, with the acceleration of electrification in the transport sector, the adoption of new energy vehicles continued to expand, while the consumption of conventional fuels such as gasoline and diesel declined significantly. At the same time, the share of electricity in transport energy consumption gradually increased. This shift is consistent with the broader direction of increasingly stringent emission reduction measures,

and the contribution of end-use electrification to carbon mitigation has become progressively more prominent, fully demonstrating the remarkable achievements of the transport sector in its low-carbon transition.

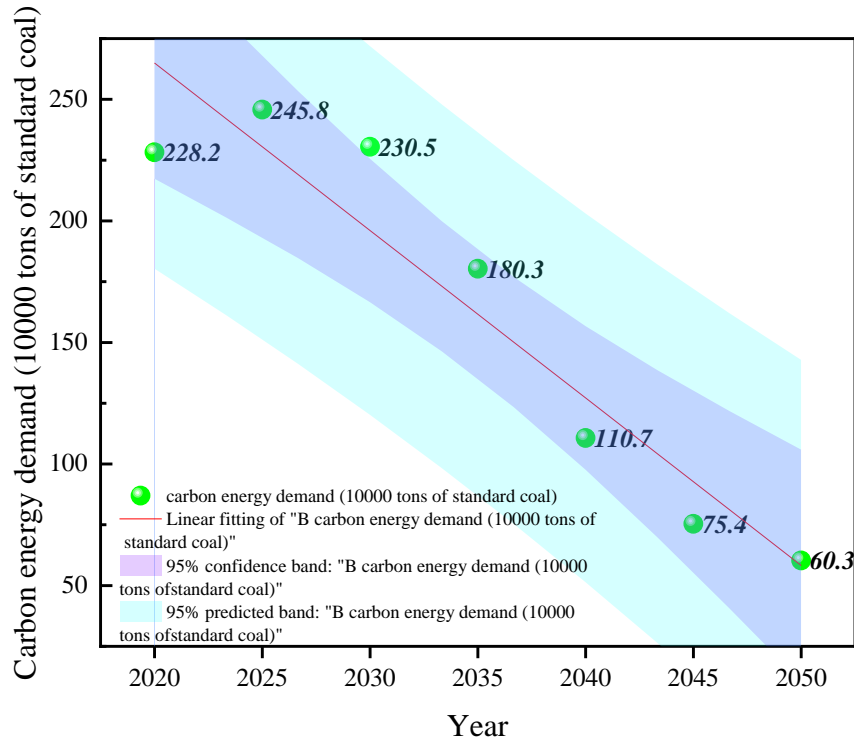


Fig 5-2 Summary of Energy Demand in the Transportation Sector

As shown in Figure 5-3, energy demand in the service sector exhibits a steady upward trend from 2020 to 2050. It increases gradually from 0.2948 million tce in 2020 to 0.536 million tce in 2050. This growth is mainly attributable to the continuously rising share of the tertiary industry in the economic structure, as the sustained expansion of the service sector has driven an increase in energy demand.

At the same time, the ongoing electrification of commercial activities and the widespread adoption of intelligent equipment in the service sector have significantly increased electricity consumption. This growth in energy demand is consistent with the emission reduction logic of industrial structure adjustment. It not only reflects the expansion of the service sector, but also indicates the upgrading

of its energy use patterns, demonstrating a favorable trend of coordinated development between the two.

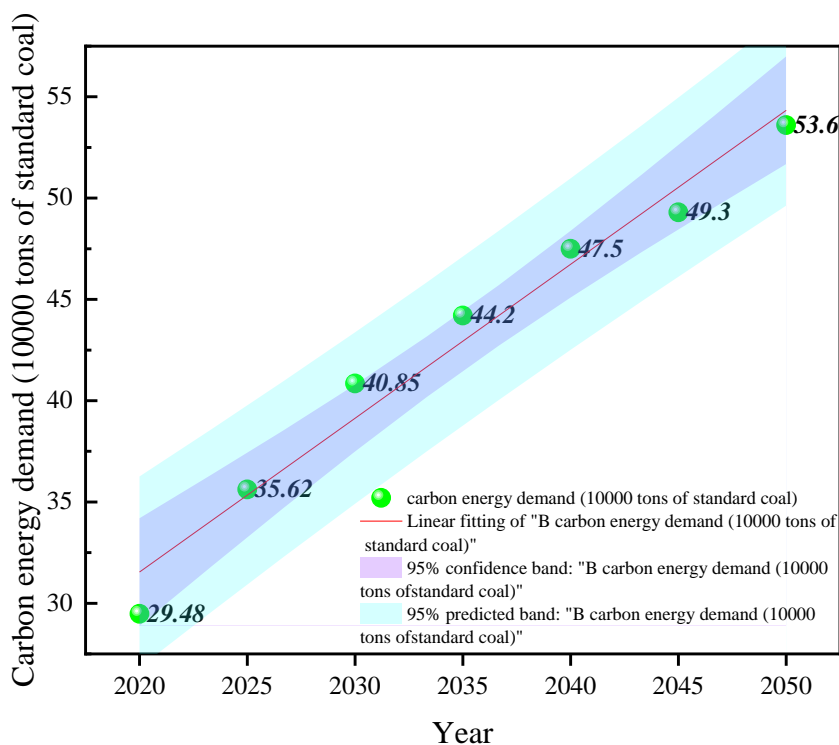


Fig 5-3 Summary of Energy Demand in the Service Sector

4 Low-Carbon Development Pathways by Sector in Huainan City

Due to differences in energy consumption structure and production and operation patterns, different sectors need to adopt targeted development pathways during the low-carbon transition. Based on the preceding forecasts of energy demand and carbon emissions, as well as the contribution rates of various mitigation measures, the low-carbon development pathways for the major sectors of Huainan, including industry, transport, and services, are analyzed as follows.

4.1 Low-Carbon Development Pathway for the Industrial Sector

As the principal contributor to both energy demand and carbon emissions, the industrial sector is central to achieving the city’s dual-carbon goals. From the perspective of development pathways, the first priority is to promote the green upgrading of energy-intensive industries. For key energy-

consuming industries such as steel, chemicals, and building materials, efforts should be accelerated to implement energy-saving technological retrofits and promote advanced technologies such as waste heat recovery and high-efficiency motors, so as to reduce energy consumption per unit of product. For example, the steel industry can promote short-process steelmaking to reduce carbon emissions from the blast furnace ironmaking process, while the chemical industry can apply carbon capture and storage (CCUS) technologies to reduce greenhouse gas emissions during production [33].

Second, optimizing the industrial energy-use structure is another important direction. The electrification level of the industrial sector should be gradually increased by replacing traditional coal-fired and oil-fired heating with electric heating, thereby reducing direct carbon emissions. Meanwhile, industrial enterprises should be encouraged to use renewable energy sources, such as biomass and geothermal energy, as auxiliary energy in the production process, so as to reduce dependence on fossil fuels. In addition, building a circular economy system can effectively improve resource utilization efficiency and reduce overall energy consumption.

4.2 Low-Carbon Development Pathway for the Transport Sector

The low-carbon development of the transport sector should take the electrification of transport vehicles as its core priority. Greater efforts should be made to promote electric cars, electric buses, and electric trucks, while improving the construction of charging infrastructure to achieve comprehensive coverage in residential areas, office districts, and public parking lots, thereby addressing users' concerns about driving range. At the same time, subsidies should be provided for the purchase of new energy vehicles, while policies such as gradual traffic restrictions and purchase restrictions on conventional fuel vehicles should be introduced to guide consumers toward the adoption of new energy vehicles.

In terms of optimizing the transport mode structure, public transportation should be vigorously developed by improving the coverage and operational efficiency of buses, metro systems, and light rail, thereby encouraging residents to prioritize public transport. In addition, green travel modes

such as bike-sharing and car-sharing should be promoted to reduce the frequency of private car use and lower energy consumption and carbon emissions in the transport sector.

4.3 Low-Carbon Development Pathway for the Service Sector

The low-carbon development of the service sector should first focus on building energy-efficiency retrofits. For key service-sector buildings such as commercial office buildings, hotels, and shopping malls, measures should be taken to improve wall insulation, upgrade energy-efficient windows and doors, and modernize lighting systems. At the same time, intelligent building management systems should be installed to enable precise control of equipment such as air-conditioning systems and elevators, thereby reducing operational energy consumption. In addition, green building standards should be promoted, and newly constructed service-sector buildings should meet higher energy-saving requirements while prioritizing the use of low-carbon building materials and renewable energy sources.

With regard to optimizing energy use in service activities, service-sector enterprises should be encouraged to adopt energy-efficient equipment and technologies and to promote the digital transformation of services. By replacing part of offline services with online services, energy consumption associated with human mobility and physical operations can be reduced. Typical examples include the promotion of online meetings, online education, and telemedicine [34].

Table 2 Low-carbon development path of Huaian City by department

Sector	Key Direction	Specific Measures	Examples
Industrial Sector	Promote the green upgrading of energy-intensive industries	Accelerate the implementation of energy-saving technological retrofits in key energy-intensive industries such as steel, chemicals, and building materials; promote advanced technologies such as waste heat recovery and high-efficiency motors to reduce energy consumption per unit of product	Promote short-process steelmaking in the steel industry; apply CCUS technology in the chemical industry

Sector	Key Direction	Specific Measures	Examples
Industrial Sector	Optimize the industrial energy-use structure	Improve the electrification level of the industrial sector by replacing traditional coal-fired and oil-fired heating with electric heating; encourage the use of renewable energy sources such as biomass and geothermal energy	Replace coal-fired heating with electric heating; enterprises use biomass energy as an auxiliary energy source
		Promote material recycling among enterprises within industrial parks and realize the resource utilization of waste	Use steel slag as raw material for building materials; chemical enterprises utilize surplus heat internally
Transport Sector	Promote the electrification of transport vehicles	Promote electric vehicles and electric buses, improve charging infrastructure, provide subsidies for new energy vehicles, and impose traffic and purchase restrictions on conventional fuel vehicles	Achieve full coverage of charging facilities in residential and office areas; provide subsidies for the purchase of new energy vehicles
		Optimize the transport mode structure	Develop public transport, improve its coverage and operational efficiency, and promote green travel modes such as shared bicycles
Transport Sector	Develop a low-carbon logistics system	Promote the new-energy transition and large-scale deployment of freight vehicles, optimize freight routes, and encourage lower-carbon transport modes such as rail and waterway transport	Promote new-energy freight vehicles; reduce the share of road freight and develop multimodal transport
Service Sector	Promote building energy-efficiency retrofits	Carry out energy-saving retrofits for commercial buildings and promote green building standards	Improve wall insulation and upgrade lighting systems in commercial buildings

Sector	Key Direction	Specific Measures	Examples
Service Sector	Optimize energy use in service activities	Encourage service enterprises to adopt energy-efficient equipment and technologies and promote the digital transformation of the service sector	Use energy-efficient kitchen equipment in the catering industry; promote online education and similar service models
	Promote green consumption concepts	Raise low-carbon awareness through publicity and education, encourage consumers to choose low-carbon products and services, and encourage enterprises to launch low-carbon service packages	Encourage consumers to bring their own shopping bags; provide discounts for low-carbon consumption practices

5 Conclusions and Recommendations

5.1 Conclusions

This study systematically simulated the dynamic trends of energy demand and carbon emissions in Huainan from 2022 to 2050 using the LEAP model, and revealed three major findings.

First, the intensity of policy intervention directly determines the effectiveness of the low-carbon transition. Under the baseline scenario, due to the continuation of the traditional development model, both energy demand and carbon emissions continue to rise. The carbon peak occurs later than the national 2030 target, reaching as high as 89.625 million tCO₂-eq, which makes it difficult to support the implementation of the dual-carbon strategy. Under the development scenario, a carbon peak is achieved in 2031 through moderate mitigation measures; however, carbon emissions still reach 52.163 million tCO₂-eq in 2050, leaving a significant gap from the carbon neutrality target. By contrast, under the enhanced low-carbon scenario, the combination of high-intensity policy measures not only enables an earlier peak in 2029 (with a peak value of 68.923 million tCO₂-eq),

but also reduces carbon emissions by 58.3% in 2050 compared with the baseline scenario, thereby providing a feasible pathway toward carbon neutrality.

Second, energy structure transformation and efficiency improvement constitute the core driving forces for emission reduction. Power sector decarbonization (contribution rate: 42.6%), end-use electrification (23.5%), and energy efficiency improvement (21.8%) together contribute more than 87% of the total emission reductions, highlighting that renewable energy substitution, greater penetration of electricity at the end-use level, and reductions in energy consumption per unit of output are the three major pillars of Huainan's low-carbon transition.

Third, the emission reduction potential of key sectors is concentrated in industry and transport. Under the baseline scenario, these two sectors account for more than 70% of total carbon emissions. Under the enhanced low-carbon scenario, through technological upgrading and structural adjustment, their emission reduction potentials reach 32.7% and 30.9%, respectively, making them the key breakthrough areas for achieving carbon peaking and carbon neutrality.

5.2 Recommendations

(1) Optimize the industrial structure of Huainan by prioritizing the development of high-tech industries and phasing out outdated industrial capacity.

(2) Optimize the energy structure by improving the level of electrification and increasing the share of clean energy sources such as hydrogen energy, wind power, and solar energy.

(3) In sectors such as industry, transport, and services, low-carbon development goals can be achieved by increasing the end-use electrification rate, reducing carbon emissions per unit of output, and improving energy efficiency. In view of the industrial characteristics of coal resource-based cities, the industrial sector may further promote low-carbon substitution of coal-based feedstocks (for example, replacing part of coal consumption with biomass fuels), while the transport sector may prioritize the electrification of freight vehicles in response to coal transportation demand.

(4) For the power generation sector, efforts should be made to expand the installed capacity of renewable energy generation, develop new power generation technologies, accelerate the application of CCUS technology, and improve the efficiency of thermal power generation, while fully utilizing Huainan's resource advantages, such as constructing photovoltaic power stations in coal mining subsidence areas. This study further proposes, for the first time, the concept of "transforming disadvantaged resources" in coal resource-based cities. Specifically, coal mining subsidence areas (traditionally regarded as disadvantaged land resources) can be converted into sites for photovoltaic power station construction, while coal gangue (traditionally treated as waste) can be utilized as an auxiliary fuel for biomass-based power generation, thereby achieving the dual benefits of emission reduction and resource recycling. For Huainan, existing coal mining subsidence areas (covering approximately 160 km²) could be used to plan photovoltaic power stations, with an estimated additional installed capacity of more than 2 million kW. For similar coal resource-based cities such as Pingdingshan and Jiaozuo, which also face large areas of subsidence land and accumulated coal gangue, this "disadvantaged resource transformation" model may be directly adopted to reduce mitigation costs while simultaneously addressing longstanding environmental problems.

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