

A Three-Dimensional “Government–Power–Carbon” Collaborative Optimization Framework for Energy-Intensive Industrial Parks

Mengyao Ren^{†,*} and Miao Shi[†]

Business School, Xi'an International Studies University, Xi'an 710128, China

[†]*These authors contributed equally to this work and share first authorship.*

**Corresponding author: Mengyao Ren.*

Abstract

Under the guidance of the “dual carbon” strategic goals, high-energy-consuming industrial parks, as the main carriers of industrial energy consumption and carbon emissions, are confronted with multiple challenges such as low energy utilization efficiency, increasingly strict carbon emission constraints, and slow policy responses. Traditional single governance approaches are unable to effectively coordinate the complex relationships among government regulation, power resource allocation, and carbon market mechanisms, thus there is an urgent need to establish a multi-dimensional mechanism coupling system optimization model. This paper focuses on the three-dimensional synergy of “government-electricity-carbon”, and constructs a collaborative optimization mechanism centered on the management organization layer, power system layer, and carbon flow network layer, exploring the path to achieve the maximization of resource allocation efficiency and the coordinated attainment of carbon emission control targets in high-energy-consuming industrial parks. To verify the feasibility of the mechanism, this paper takes the high-energy-consuming industrial park of Henan Luoyang Petrochemical as a case, and conducts simulation and comparative analysis based on on-site energy consumption and emission data. The research results show that this mechanism strengthens the dynamic regulatory role of government policies, enhances the response flexibility of the power system and the price discovery function of the carbon market. It not only provides theoretical support and practical paths for the low-carbon development of high-energy-consuming industrial parks, but also has significant practical significance and promotion value for achieving the carbon peak and carbon neutrality goals within the regional scope.

Keywords

high-energy-consuming industrial parks, “government-electricity-carbon” collaborative mechanism, low-carbon transformation, dual carbon goals

1. Introduction

With the in-depth promotion of China's strategy of “striving to reach the peak of carbon dioxide emissions by 2030 and striving to achieve carbon neutrality by 2060” (hereinafter referred to as “dual carbon”), the industrial field has become a key battlefield to achieve the goal of carbon emission reduction. As the core

carrier of industrial energy consumption and carbon emissions, the carbon emission intensity of high-energy-consuming parks is high, which has become the focus and difficulty in achieving the “dual carbon” goal. Take Henan Province, a large industrial province, as an example. According to the latest data, the total industrial carbon emissions account for more than 60% of the province [1], among which the proportion of carbon emissions in high-energy-consuming parks is as high as 45%, and the carbon intensity is significantly higher than the national average [2].

At present, these parks are generally caught in the development paradox of “increasing production means increasing carbon, and reducing carbon is afraid of losing money”: on the one hand, with the expansion of production scale, the rigid increase in energy consumption directly leads to an increase in carbon emissions [3]; on the other hand, the implementation of compulsory carbon emission reduction measures will significantly increase the operating costs of enterprises and affect economic benefits. This contradiction has become a profound problem that restricts the green and low-carbon transformation of China's industry, and an innovative solution is urgently needed.

In-depth analysis shows that the root cause of this dilemma is not only the relative lag of technical equipment, but more importantly, the systemic rupture in the governance system of high-energy-consuming parks. Specifically, it is manifested in the coordination failure of the three dimensions of “government” (management organization layer, responsible for policy formulation and transmission), “electricity” (power system layer, responsible for energy scheduling and implementation), and “carbon” (carbon flow network layer, responsible for carbon emission accounting and constraints), forming a triple rigid constraints: first, there is a significant attenuation of the policy transmission mechanism, and it is difficult to accurately implement policies such as emission reduction targets, carbon quota allocation and green electricity incentives formulated by the government [4]; second, the scheduling optimization of the power system mainly focuses on electricity prices and load signals, and generally ignores the key impact of carbon emission constraints [5]; third, carbon emission management still adopts static annual accounting method, lacks real-time monitoring and dynamic feedback capabilities, and cannot support accurate energy decision-making and policy adjustment. This state of independent governance and lack of linkage makes it difficult to find a systematic solution at the park level that takes into account the goals of economic development and carbon emission reduction.

In response to the above problems, this paper innovatively builds a three-dimensional collaborative closed-loop optimization mechanism of “management organization-power system-carbon flow network” (referred to as M-E-C), and establishes a refined energy and carbon emission response system through the organic integration of the three key links of “policy transmission - energy scheduling - carbon emission control”. This study selects Henan Luoyang Petrochemical High Energy Consumption Park as a typical empirical case, and carries out systematic simulation and comparative analysis based on multi-source data (policy text, energy consumption data, carbon emission data). At the technical level, integrating LSTM and random forest algorithms to achieve high-precision load prediction, and improve the NSGA-II algorithm to support multi-target scheduling optimization with carbon quota constraints; at the institutional level, design carbon intensity dynamic assessment and green power premium mechanism to promote the transformation of enterprises from “passive fulfillment” to “active emission reduction”.

Through this innovative mechanism, this research aims to realize the coordinated optimization of power system dynamic scheduling and carbon emission costs, which not only directly responds to the national “dual carbon” strategic needs, but also provides a green transformation path that is economically feasible, technically reliable and policy-effective for more energy-consuming parks. The research results have important theoretical value and practical guidance to promote low-carbon development in the industrial field.

2. Literature Review and Practical Analysis

2.1 Literature Review

2.1.1 The Evolution and Limitations from “Electricity-Carbon Synergy” to “Government-Electricity-Carbon” Three-Dimensional Governance

Driven by the “dual carbon” goal, high-energy-consuming parks have become a key node to realize the green and low-carbon transformation of industry due to their large energy consumption, strong carbon

emissions and concentrated load. The current research has gradually formed a research framework with “technical coordination” and “market coupling” as the main line, and has made remarkable progress in the bilateral coupling of power system optimization and carbon market mechanism.

In terms of the electricity-carbon synergy mechanism, Yi Jun et al. [6] proposed a synergistic control system that includes indirect emission reduction assessment and electricity carbon accounting, expanding the analytical boundaries of energy systems under carbon constraints. Xiao Bai et al. [7] incorporated carbon trading factors into the power dispatch model, preliminarily achieving dual-objective optimization of economy and emission reduction. Ji Xingquan et al. [8] emphasized the synergistic configuration of low-carbon and economic objectives. These studies theoretically advanced the establishment of the electricity-carbon coupling analysis framework, but most of their models were based on a single system optimization paradigm, did not involve the policy transmission mechanism among the governance entities of the park, and failed to fully consider the regulatory role of the institutional structure on the evolution path of carbon flows. When facing the “triple disconnection” situation of policy transmission absence, power dispatch carbon constraints failure, and carbon management response delay in high-energy-consuming parks, they still lacked structural solutions.

2.1.2 Research At the Park Level: Deepening and Bottlenecks of Market Mechanisms and Enterprise Behaviors

In the research at the park level, the electricity-carbon market mechanism and enterprises' emission reduction behaviors have become the focus. The existing studies present two main characteristics: Firstly, the design of market mechanisms has become the mainstream direction. Zhang Guoliang et al. [9] constructed a coupled model of electricity-carbon-green certificate market, verifying its role in improving resource allocation efficiency; Dong Jiuzhou et al. [10] pointed out that electricity-carbon trading needs to be coordinated with the green certificate mechanism to motivate enterprises to decarbonize; Li Xianshan et al. [11] proposed a quota and CCER offset mechanism, optimizing the carbon cost control path. However, most of the aforementioned studies focused on the optimization of the market level itself, neglecting the institutional constraints and incentive effects of management organizations (such as the government, park management committees) on enterprises' behaviors, and failing to deeply integrate the market mechanism with the policy system. Secondly, research on the response of enterprise behaviors has begun to attract attention. Zhang Lingrong et al. and Liu Peide et al. [12-17] used evolutionary game theory and closed-loop supply chain models to precisely depict the micro-decision-making mechanism of enterprises under carbon price signals. However, the conclusions of these models are often difficult to extrapolate to the macro system design at the park level, and their deep real-time linkage with the power system is still insufficient.

2.1.3 Limitations of the Two Main Lines of “Technological Synergy” and “Market Coupling”

It is worth noting that the existing research has formed two relatively clear main lines of “technical coordination” and “market coupling”, but both of them have the problem of missing dimensions:

At the level of technical coordination, Liu Hao et al. [18] put forward a coordinated scheduling model for landscape carbon storage to improve user satisfaction by dynamically constraining carbon emissions; Hong Mingzhi et al. [19] built a carbon reduction model of waste heat cascade utilization to verify the economic and environmental protection benefits of industrial multi-energy flow coordination. However, these studies do not sufficiently portray the dynamic coupling mechanism of power system and carbon flow, and do not consider the regulatory effect of policy transmission on the selection of technical paths.

In the direction of market coupling, Li Lingfang et al. [20] designed a micro-grid cluster electricity-carbon collaborative trading structure in the industrial park, which effectively reduced operating costs; Huang Ying et al. [21] built a multi-scale decision-making model of power generation group electricity-carbon. However, its optimization dimension is still limited to the main interaction at the enterprise or group level, which fails to solve the problem of incentive transmission fault of “policy-enterprise” in the park.

The deeper common limitation lies in the lack of cross-level coordination mechanisms. For example, although Xu Zhenhua et al. (2025)'s [22-23] source network load reserve coordination model adopts robust optimization to respond to new energy fluctuations, carbon quota constraints are still dominated by static annual accounting; Chen Huixin et al.'s [24] pollution reduction and carbon reduction multi-objective optimization proves the effectiveness of the NSGA-II algorithm, but does not quantify the impact of the policy

coordination of management (such as government-park-enterprises) on the technical path; Hou Jingyi et al. [25] put forward the concept of pollution reduction and carbon reduction coordination, but lacks the design of the “electricity-carbon intensity double constraint” dynamic conduction mechanism unique to high-energy-consuming parks.

2.1.4 Theoretical Innovation Points

In conclusion, although the current research has achieved significant results in the field of electrocarbon synergy, when dealing with the practical predicament of high-energy-consuming industrial parks where “increasing production leads to increased carbon emissions and reducing carbon emissions may result in losses”, there are still two core deficiencies: Firstly, the existing coupling mechanisms lack dynamic interactivity and policy transmission paths, resulting in a sluggish response from the government to enterprises regarding carbon reduction requirements, and the synergy effect between policies, scheduling, and carbon management has not been fully exerted; Secondly, the current research mainly focuses on theoretical exploration and model construction, lacking empirical studies and multi-source data support for high-energy-consuming industrial parks.

Based on this, this study aims to construct a three-dimensional dynamic optimization model that connects policy formulation, power implementation, and carbon emission control, consisting of a “management organization layer (M), power system layer (E), and carbon flow network layer (C).” The innovations of this paper are: in terms of theoretical framework, it introduces Social Network Analysis (SNA) to quantify “policy synergy,” bridging the research gap between “institutional and behavioral” aspects in traditional models from a governance perspective; in terms of technical methods, it integrates LSTM and random forest to achieve high-frequency load forecasting and improves the NSGA-II algorithm to support multi-objective optimization with dynamic carbon constraints, realizing real-time linkage between “source-grid-load-storage”; in terms of system integration, it strives to open up the key closed-loop path of “institutional-technology-market,” providing a theoretically closed-loop and practically implementable systematic solution to overcome the dilemma of three-dimensional fragmentation.

2.2 Practical Analysis

To gain a deeper understanding of the practical pathways, achievements, and bottlenecks in the coordinated governance of electricity and carbon emissions in high-energy-consuming industrial parks, this study selects representative industrial parks in Guangdong and Jiangsu provinces, which excel in policy mechanism innovation and technology integration, for in-depth case analysis. While these cases have achieved significant progress, they also reveal common challenges, providing important practical insights and optimization directions for constructing the three-dimensional coordinated governance framework in this paper.

2.2.1 Case One: A High-tech Industrial Development Zone in the Pearl River Delta of Guangdong Province

Currently, a deep coupling of the “electricity-carbon-green certificate” market has been achieved [26-28], deeply integrating park-level carbon quota trading, direct green electricity trading, and green certificate subscription mechanisms. Enterprises can sell excess carbon quotas through the park's internal trading platform, and the proceeds can be directly used to offset the premium for green electricity procurement or to purchase green certificates, forming a closed-loop incentive of “emission reduction-increased revenue-further emission reduction”. The park management committee, in collaboration with China Southern Power Grid and the carbon exchange, has established a unified 'Electricity-Carbon Coordinated Trading Platform,' achieving data interoperability and one-stop trading. At the same time, the park has introduced dynamic carbon price signals to guide load adjustments. When the ratio of real-time to expected carbon prices exceeds a set threshold, it will automatically trigger optimized operation strategies for high-energy-consuming adjustable loads (such as air conditioning systems), or increase energy storage discharge, reducing operational costs and carbon emissions during periods of high electricity and carbon prices. The proportion of enterprises participating in green electricity trading increased from 15% at the beginning of the pilot program to 45%, with green electricity consumption growing at an average annual rate of 32%. Some enterprises have increased their annual revenue by over one million yuan through carbon quota trading, effectively offsetting some of the transformation costs. The carbon emission intensity per unit of output in the industrial park has also decreased by about 12% within two years, and the green electricity penetration rate has increased to 25%. This model has also been promoted

by the National Development and Reform Commission as a typical experience due to its clear market-oriented incentive mechanism.

2.2.2 Case Two: A National-level Economic and Technological Development Zone in Southern Jiangsu Province

Nowadays, this development zone in Jiangsu Province has implemented a “management - technology - platform” tripartite model, led by the park management committee and established as the “Electricity and Carbon Smart Operation Center”. It integrates power grid dispatch data, enterprise energy consumption data, and online environmental monitoring data (CEMS) to build a unified “Electricity and Carbon Digitalization Platform”. This platform can already achieve multiple functions such as precise carbon profiling, coordinated optimization of source, grid, load, and storage, dynamic monitoring and early warning of carbon intensity, etc. By leveraging digital technology to enhance management coordination, the initiative provides the Management Committee, the power grid company, and key enterprises with a platform for data sharing and collaborative decision-making, thereby improving the efficiency of policy communication and implementation. The installed capacity of energy storage systems in the park has also doubled within two years, making them a vital source of flexibility.

2.2.3 Summary and Implications of Practical Analysis

Based on the practices of the leading parks in the two provinces, we can clearly see the progress and achievements of the two provinces: through market mechanism innovation (Guangdong) or technology platform integration (Jiangsu), significant results have been achieved in improving green electricity consumption, reducing carbon intensity, exploring the economics of energy storage, and improving management coordination, which has verified the feasibility and potential of electricity-carbon synergy optimization.

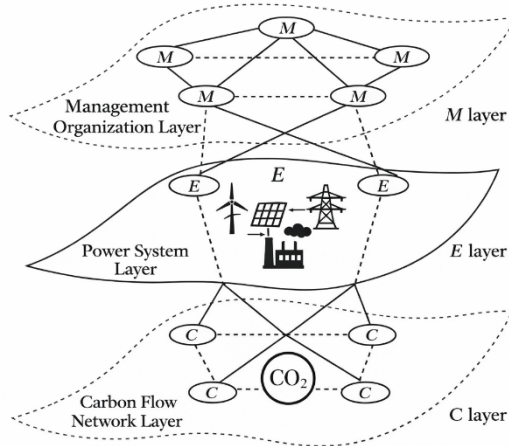
However, common shortcomings still exist, specifically: the three-dimensional separation remains a bottleneck. Both cases reflect that insufficient coupling between the “management organization layer (policy coordination, resource integration) - power system layer (source-grid-load-storage coordination) - carbon flow network layer (precise carbon emission control and constraint)” is the key factor restricting efficiency improvement; incentive compatibility needs to be strengthened: how to more effectively and rigidly transmit carbon costs to the micro-decision-making level of enterprises and design sufficiently strong economic incentives, especially in terms of reducing green electricity costs and increasing energy storage revenue, is a problem to stimulate enterprises' endogenous emission reduction motivation.

3. Construction of Three-dimensional Network Model Mechanism

3.1 Construction of A Collaborative Optimization Mechanism for the “Government-Electricity-Carbon” Three-dimensional Network

The synergistic optimization of the electricity-carbon system in high-energy-consumption industrial parks primarily involves three core dimensions: the power system (E), the carbon flow network (C), and the management organization (M). In current practice, E and C often independently optimize around “energy supply efficiency” and “emission accounting” respectively. The assessment and incentives at the M level fail to form a continuous and measurable transmission link. There is a lack of effective dynamic coupling among the three, resulting in the disconnection of prices, constraint signals and operational decisions, making it difficult to achieve the coordinated goal of “optimal energy allocation and precise carbon emission control”. For this reason, this paper builds a three-dimensional hypernetwork model (Figure 1) including the management organization layer (M layer), the power system layer (E layer) and the carbon flow network layer (C layer) for the park scenario, and designs a closed loop of “policy flow-energy flow-carbon flow”: realizes the continuous transmission of policy flow to the decision-making of the source network load storage with dynamic carbon strength and electricity and carbon price linkage, and the carbon flow formed by the operation results is fed back to the policy and scheduling side in real time to form an observable and calibrated coordination mechanism. The three-layer network model is shown in Figure 1 below:

Figure 1: Three-dimensional network collaborative optimization model of Management Organization Layer - Power System Layer - Carbon Flow Network Layer



3.1.1 Management Organizational Layer: Multi-subject Collaborative Mechanism

The three-dimensional collaborative optimization of “government-electricity-carbon” in high-energy-consuming parks is highly dependent on the effective transmission and integration of the management organization layer. The core subjects of the M level include government supervision (the Development and Reform Commission, the Department of Ecology and Environment), park operation (management committee), and the main body of enterprises (high-energy-consuming enterprises, energy service providers). In reality, policy fragmentation and inefficiency of resource integration are common. The former is manifested in the inconsistent caliber of policy goals, the dispersion of tools, and the mismatch of timing; the latter is manifested in the low efficiency of cross-departmental and cross-enterprise matching of data, funds, indicators and other factors between the main subjects. In order to identify and quantify the above constraints, this study constructs two core indicators at the M level: policy coordination P_c and resource integration efficiency C_d .

Because there are often differences in ambiguity, graduality and compatibility in the expression of policy objectives, in order to maintain the consistency of policy objectives, the policy synergy is calculated by fuzzy set theory, and the calculation formula is shown in (1):

$$P_c = \frac{\sum_{i=1}^n \cdot \sum_{j=1}^m \mu_{A_i}(x) \cap \mu_{B_j}(x)}{n \times m} \tag{1}$$

μ_{A_i}, μ_{B_j} , are the target membership functions of policy A and policy B, respectively. At the same time, this paper uses the “centrality” index C_d in social network analysis to measure the efficiency of resource integration, and calculates the normalized value of the sum of the inverses of the shortest paths between all nodes in the network, as shown in formula (2), so that the overall compactness of the network is more accurate.

$$C_d = \frac{\sum_{i=1}^N \cdot \sum_{j=1}^N d(i, j)^{-1}}{N(N-1)} \tag{2}$$

$d(i, j)$ is the shortest path length between nodes i and j and N is the total number of nodes. If the C_d value is greater than 0.7, the average path for information/resource transmission is shorter and more efficient, and the network is highly integrated; if the C_d value is less than 0.4, the average path is longer, the network will fragment, and the transmission of resources will be severely hindered.

3.1.2 Power System Layer: Source-Grid-Load-Storage Collaborative Model

As the physical carrier of the three-dimensional model, the E layer needs to realize the real-time linkage of energy flow dynamic optimization and carbon emission control. The model is built around the four types of objects of “power supply-power grid-load-energy storage”:

(1) Power supply side: Due to the timing dependence and meteorological sensitivity of photovoltaic output, this study integrates distributed photovoltaics, self-provided power plants and other multi-energy supply, and uses the LSTM-random forest combination model to predict the photovoltaic output to improve the prediction accuracy. The formula is shown in (3):

$$P_{pv,t} = f \left(\begin{array}{c} LSYM(X_{t-n}, \dots, X_t) \\ RandomForest(T_t, G_t, V_t) \end{array} \right) \quad (3)$$

X_t is historical data, T_t is temperature, G_t is total horizontal irradiance, V_t is wind speed.

(2) Load side: Based on the principle of economy, this study also needs to consider the balance of scheduling flexibility and default cost. Therefore, a time-break response model of high-energy-consuming load $L_h(t)$ and adjustable load $L_a(t)$ is established on the load side, and the load interruption punishment item $P_p(t)$ is introduced. The punishment coefficient λ_t dynamically correlates the time-consuming electricity price with the carbon price, and drives the enterprise to actively adjust the adjustable load. The formula is shown in (4):

$$P_p(t) = \lambda_t \times (L_h(t) - L_{scheduled}(t)) \quad (4)$$

λ_t is the penalty coefficient for period t , $L_{scheduled}(t)$ is the rigid load demand.

(3) Energy storage side: Because the strong coupling relationship between charge and discharge power $P_{ch,d,t}$ and the charge state SoC_t will directly affect the stability of the system, the accurate modeling of the rated capacity E_r and efficiency η will be the prerequisite for ensuring the economy of energy storage. Based on the system characteristics of energy storage of lithium iron phosphate batteries in the energy storage system, this study constructs the charging and discharging state equation. The formula is shown in (5):

$$SoC_t = SoC_{t-1} + \eta \times \frac{P_{ch,d,t} \times \Delta t}{E_r} \quad (5)$$

E_t is the charge state at time t , η is the efficiency, $P_{ch,d,t}$ is the charging and discharging power, E_r is the rated capacity.

3.1.3 Carbon Flow Network Layer: Multi-dimensional Carbon Flow Accounting System

The core bottlenecks at the C layer of the electricity-carbon synergy in high-energy-consuming parks mainly lie in two aspects: First, the carbon cost accounting is static, with annual verification as the main approach, resulting in a mismatch between the scope, timeliness and operational decision-making. Second, the transmission of emission reduction targets is disconnected, and the target and price signals are difficult to be internalized into time-of-use scheduling. The industrial park frequently conducts annual carbon audits, which cannot respond to the real-time dispatching needs of the power system, resulting in a disconnect between the “electricity-carbon” system. To address this, this study constructs a three-tiered progressive mechanism based on the “production-consumption-trading” model, namely “accurate accounting → dynamic targets → endogenous incentives,” to streamline the transmission path from carbon constraints to energy decision-making.

The specific three-level collaborative mechanism is designed from three dimensions: carbon footprint accounting, carbon quota constraints, and carbon trading mechanisms.

In carbon footprint accounting, based on the characteristics of high-energy-consuming industrial parks that combine indirect emissions from electricity generation and emissions from industrial processes, this study sets localized factors according to the “Guidelines for Carbon Emission Accounting of Key Industries in Henan Province” to achieve provincial standard adaptation. Meanwhile, to avoid errors from a single method, this study adopts a hybrid accounting framework of “emission factor method + mass balance method”. The specific accounting formula is shown in (6):

$$C_t = \sum(E_t \times \gamma_e) + \sum(Min, t - Mout, t) \quad (6)$$

E_t is the activity data (electricity consumption), γ_e is the carbon emission factor of electricity, $Min, t/Mout, t$ is the carbon quantity of material input and output.

In terms of carbon quota constraints, in order to respond to the mandatory emission reduction requirements of the “Implementation Plan for Carbon Peaking in the Industrial Sector of Henan Province” and convert the static annual quota into a decreasing intensity threshold year by year, this study introduces a dynamic carbon intensity threshold calculation formula, as shown in (7):

$$C_{int,t} = C_{base} \times (1 - \alpha)^t \quad (6)$$

C_{base} is the reference carbon intensity, α is the annual reduction coefficient, t is the target year.

In terms of carbon trading mechanism, this study is linked with the market to build a cost optimization model under carbon price fluctuations, and uses the carbon price threshold (see (8) for the calculation formula) to trigger the coordinated scheduling of source network load storage. Reflect the product effect of quota gap and real-time carbon price in electricity consumption decision-making, and drive enterprises to achieve cost optimization through load adjustment.

$$C_{cost} = (E_t \times \gamma_e - Q_t) \times P_c(t) \quad (7)$$

E_t is electricity consumption, Q_t is carbon quotas, $P_c(t)$ carbon prices.

3.2 Data Platforms and Technical Tools

Data storage: Use MySQL to build a three-dimensional database, set up “policy management”, “energy flow” and “carbon flow” sub-tables, and realize cross-layer data association through a unique enterprise code (unified social credit code).

Analysis tools: Python (NLTK) is used for management data processing, MATLAB (optimization toolbox) is used for power and carbon data modeling, and Tableau is used for visualization.

3.3 Three-dimensional Network Coupling Optimization Model

The improved NSGA-II algorithm is adopted to solve the dual-objective optimization problem of economy and carbon emissions, and the objective function is:

$$\min(C_{total}, ECO_2) = \min(\sum t = 1T(C_{elec}, t + C_{ES}, t + C_{carbon}, t), \sum t = 1TEtCI_t) \quad (9)$$

Among them, C_{elec}, t is the cost of time-of-use electricity pricing, C_{ES}, t is the operation and maintenance cost of energy storage, CI_t is the carbon intensity factor of the time period.

The following are the constraints:

Balance of power supply and demand:

$$PPV, t + P_{coal}, t + P_{grid}, t = L_{high}, t + L_{flex}, t + P_{ES}, t \quad (10)$$

Among them, P_{PV}, t represents the photovoltaic power output in period t ; P_{coal}, t represents the coal-fired unit output in period t ; P_{grid}, t the grid purchase electricity in period t ; L_{high}, t represents the high-energy-consuming rigid load in period t ; L_{flex}, t represents the adjustable load in period t ; P_{ES}, t : the power of energy storage charging and discharging in period t (charging is negative, discharging is positive).

Energy storage operation boundary:

$$SoC_{min} \leq SoC_t \leq SoC_{max} \quad (11)$$

Among them, SoC_t represents the battery charge state (in percentage) of the energy storage at time period t ; SoC_{min} is the minimum allowable charge state of the energy storage; SoC_{max} is the maximum allowable charge state of the energy storage.

Carbon intensity constraint:

$$CI_t \leq CI_{threshold, t} \quad (12)$$

Among them, CI_t represents the actual carbon intensity of period t ($tCO_2/100,000$ yuan of output value); $CI_{threshold, t}$ represents the carbon intensity threshold of period t ($tCO_2/100,000$ yuan of output value).

The model optimizes population diversity through the cross-entropy method, introduces elite retention strategies to improve the convergence speed, and finally generates the Pareto optimal solution, as shown in Table 1 below:

Table 1: Pareto final optimal solution set table

Total CO ₂ (Mt)	Unevenness (standard deviation)	Power proportion	Industry proportion	Ground Transport proportion
30.139886	15.23%	40.12%	31.64%	8.46%
27.585202	12.89%	43.85%	39.18%	9.81%
28.615207	14.02%	41.76%	35.92%	8.82%
26.821532	13.45%	43.21%	36.75%	9.12%
28.439863	14.56%	42.15%	38.01%	8.93%

4. Empirical Analysis and Results

4.1 Case Selection and Data Source

This study selects the national high-energy-consuming park of Petrochemical in Luoyang District, Henan Province as a typical research object. The industrial structure of the park covers typical high-energy-consuming industries such as electrolytic aluminum, steel and chemical industry. Its high-energy consumption and high-carbon emission characteristics are significantly representative in high-energy-consuming parks in Henan Province, which provides a solid foundation for the typicality and universality of the research conclusion. The time span of the research data is set to 2019-2024, and a comprehensive and timed data system is built.

In the data collection link, this study has established a systematic data architecture covering multiple dimensions and sources. The data at the management organization level mainly includes 89 policy documents issued by the park management committee. Through text mining and content analysis technology, the orientation and implementation path of policy formulation are deeply analyzed. At the same time, 120 carbon management questionnaires are distributed to enterprises in the park to obtain policy response and implementation from the enterprise practice level, and provide micro perspective support for policy coordination and resource integration efficiency analysis. The power system layer data covers the time-by-time electricity consumption data from 2019 to 2025. Relying on the smart meter system, more than 95% of the electricity consumption equipment in the park can be monitored in real time to achieve accurate capture of energy consumption dynamics; the actual measurement data of photovoltaic output has been calibrated by NASA POWER meteorological data, which significantly improves the accuracy of new energy power generation forecast; the dispatch data of Henan power grid sets boundary conditions for demand-side response research. In terms of carbon flow network layer data collection, based on the enterprise carbon verification report, the system collects information such as fossil energy consumption, industrial process emissions and indirect electricity emissions, and combines the quota price sequence of Henan carbon market in 2023-2024, enterprise carbon quota allocation and performance data, and real-time carbon emission data of the park's carbon monitoring platform to form a complete carbon flow tracking chain.

4.2 Data Acquisition and Processing

4.2.1 Multi-source Data Acquisition System

This study builds a three-dimensional data acquisition framework covering the “management organization layer-power system layer-carbon flow network layer” to ensure the cross-dimensional coupling and timeliness of the data.

(1) Manage organizational data:

Policy texts and management documents: 127 documents including the carbon quota allocation policy for parks from 2019 to 2025 and the green electricity trading rules were obtained through government public channels (the official website of the Development and Reform Commission of Henan Province and the government affairs platform of the Department of Ecology and Environment). Semi-structured interviews (n=23) were conducted with the Management Committee of the park, the Development and Reform

Commission, and the Department of Ecology and Environment to document the key nodes and implementation obstacles in policy transmission.

Enterprise questionnaire and synergy: distribute 120 carbon management questionnaires to high-energy-consuming enterprises (electrolytic aluminum, steel enterprises) to collect the response of enterprises to policies (photovoltaic installation willingness, energy storage investment decision-making); build a synergistic matrix of “policy makers-parks-enterprises” through social network analysis tools (UCINET) to quantify the policy synergy between nodes (the intensity of the relationship between carbon quota policies and electricity price policies).

(2) Power system layer data

Real-time data of energy flow: connect to the smart meter system of the park (covering more than 95% of electricity-consuming equipment), collect time-by-time electricity consumption data from 2019-2025 (resolution 15 minutes), including photovoltaic power station output (kW), self-prepared power plant power generation (MWh), energy storage system charging and discharging power (kW) and high-energy-consuming equipment load (such as electrolytic rectifier aluminum flow unit current/voltage data).

External environmental data: synchronously obtain NASA POWER meteorological data (including irradiance, wind speed and temperature) for photovoltaic power prediction model calibration; collect Henan power grid scheduling data (such as peak and valley period division, electricity price signals), and build boundary conditions for demand-side response.

(3) Carbon flow network layer data

Carbon footprint accounting data: Based on the enterprise carbon verification report (according to the “Guideline for Carbon Emission Accounting for Key Industries in Henan Province”), collect fossil energy consumption (coal and natural gas usage), industrial process emissions (such as blast furnace gas emissions of steel smelting) and indirect electricity emissions (electricity consumption \times regional power grid carbon emission factor).

Carbon market and monitoring data: obtain the quota price sequence of Henan carbon trading market from 2023 to 2024 (28-52 yuan/ton), the carbon quota allocation and performance of enterprises; connect with the carbon monitoring platform of the park to collect real-time carbon emission data of key enterprises (through CEMS online monitoring equipment).

4.2.2 Data Processing and Integration Methods

(1) Data cleaning and preprocessing

Missing value filling: Considering the correlation of meteorological data, LSTM interpolation is used for photovoltaic output data; based on the co-occurrence matrix of policy keywords, the multiple interpolation method is adopted for the policy synergy degree data.

Abnormal value detection: use the 3σ criterion to identify abnormal fluctuations in the power load data (such as the instantaneous load increase caused by equipment failure), and verify and correct it in combination with the enterprise production log.

Digitalization of management data: extract keywords such as “carbon emission reduction target” and “subsidy strength” in the policy text through NLP technology to build a policy synergy index; use social network analysis to calculate the node center, and identify the “key intermediary node” in policy transmission.

Electric carbon data coupling: match the power flow data with the carbon flow data, and calculate the indirect carbon emissions of each electrical equipment through the current tracking algorithm to form a three-dimensional data table of “equipment-time-carbon intensity”.

(2) Data quality control

Reliability and validity testing: The policy interview data was verified through triangulation (cross-referencing documents and interview content) to ensure reliability; the electricity and carbon data were verified through equipment validation (such as regular calibration of electricity meters and comparative testing of carbon monitoring equipment) to control validity.

Collinearity handling: Perform VIF (variance inflation factor) tests on the input variables of the 3D network model, and use principal component analysis (PCA) to reduce highly correlated variables (such as electricity price and load) to a comprehensive index.

4.3 Analysis Results of Three-dimensional Network Nodes

According to data from Carbon Monitor, as shown in Figure 2, carbon emissions from the power industry in Henan Province exhibited significant seasonal fluctuations from 2019 to 2024, with double peaks in winter (January-February) and summer (June-August) due to heating and cooling demand, respectively. Notably, March and October saw emission troughs, possibly related to favorable weather and reduced electricity load. The Pareto optimal date (March 20, 2019) largely fell within these troughs, suggesting the potential value of seasonal adjustments for emission reduction.

Figure 2: The trend of daily CO₂ emissions of residents in Henan Province from 2019 to 2024

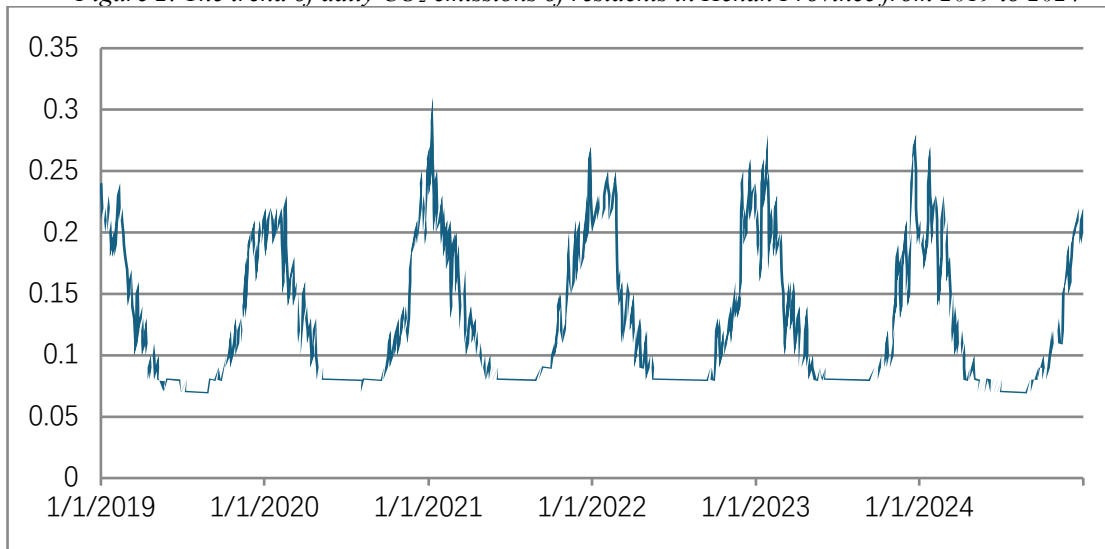


Figure 3: The daily variation trend of industrial carbon emissions in Henan Province from 2019 to 2024

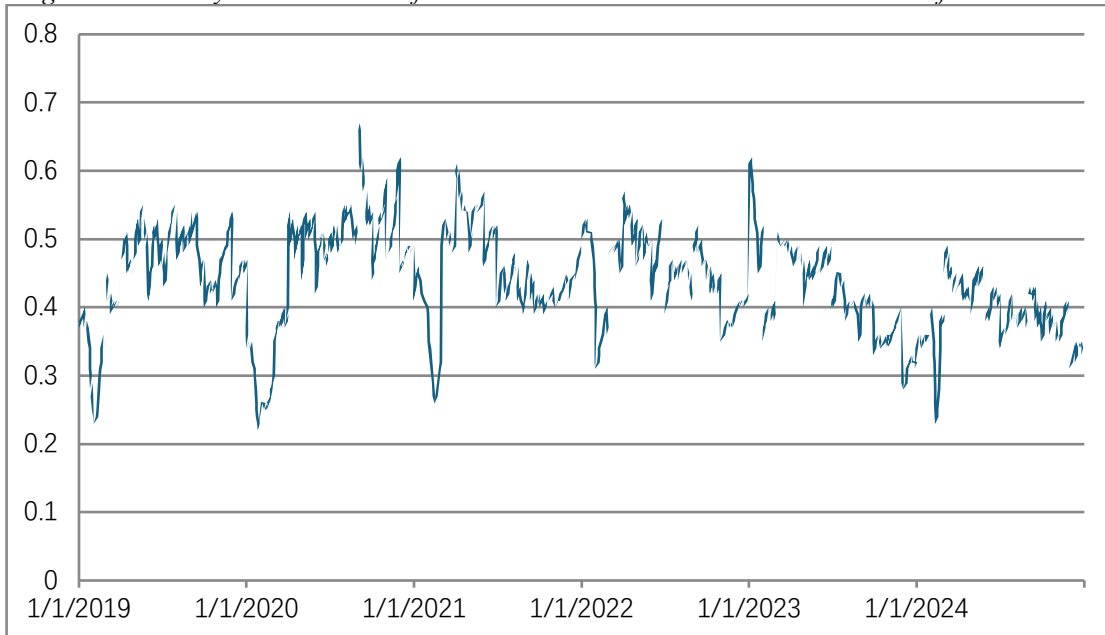
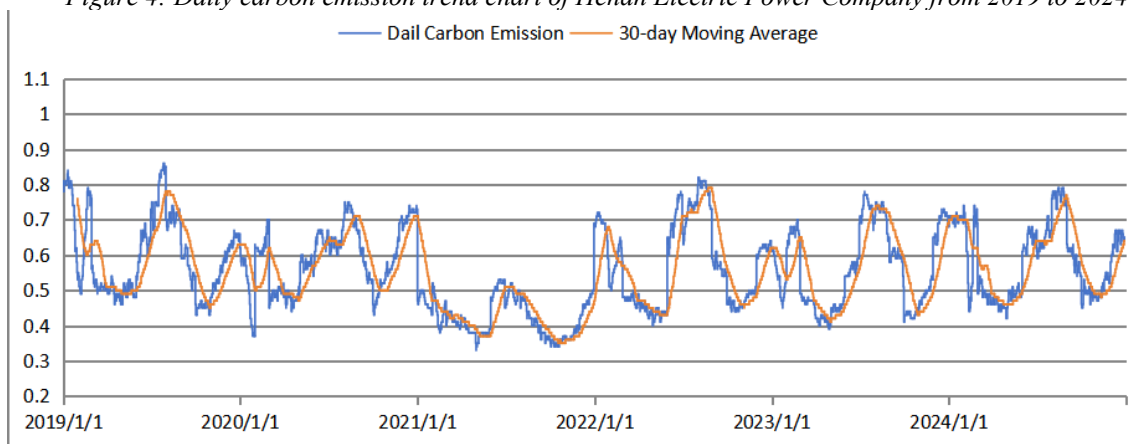


Figure 4: Daily carbon emission trend chart of Henan Electric Power Company from 2019 to 2024



4.3.1 Management Efficiency of the Organizational Layer

After quantitative analysis and measurement, the value of the policy synergy index at the management organization level P_c is 0.62, which shows that there is still significant room for optimization in the current policy system in terms of coordination mechanism. In-depth deconstruction found that the two core policies of “carbon quota allocation” and “green electricity trading” have obvious gaps in connection at the level of institutional design. The quantitative evaluation based on the semantic similarity algorithm shows that the relevance of the two policies is only 0.45, which significantly weakens the overall implementation effectiveness of the policy system. The resource integration efficiency index C_d is 0.78, Although it is at a medium level, the average path length of information transmission between the park management committee and enterprises, which is the center of policy transmission, reaches 2.3 jumps, and there are 1-2 key “structural holes” in the network topology. Such network structure defects seriously restrict the timeliness of policy transmission and the optimization process of resource allocation, resulting in the failure of the overall coordination function of the management organization level.

4.3.2 Optimization Effect At the Power System Layer

Under the three-dimensional collaborative optimization mechanism of “government-electricity-carbon”, the operation of the power system has been significantly improved in terms of economic benefits and system performance. From the analysis of economic benefits, the arbitrage income of Fenggu electricity price increased by 21.8% compared with the benchmark scenario, and the static investment recovery period of energy storage projects was shortened to 4.6 years, which effectively reduced the comprehensive energy cost of enterprises and provided a solid economic feasibility basis for investment decision-making of energy storage facilities. In terms of system performance, the consumption capacity of new energy has been significantly enhanced, the penetration rate of photovoltaic power generation has increased from 15% to 28%, the proportion of power supply load of self-provided power plants has decreased by 12 percentage points, and the peak and valley difference rate of the system has narrowed by 19%. The above optimization results show that the coordination mechanism has effectively promoted the low-carbon transformation of the power supply structure and realized the coordinated improvement of the stability and economy of the power system.

4.3.3 The Emission Reduction Achievements of the Carbon Flow Network Layer

The optimization results of the carbon flow network layer have been remarkable. The carbon intensity of the park has decreased from 1.85 tCO₂/10,000 yuan output value to 1.53 tCO₂/10,000 yuan output value, a decrease of 17.4%, which provides strong support for the low-carbon transformation of the park. Under the action of the carbon market mechanism, the carbon transaction cost is saved by 3.2 million yuan per year; the carbon emission factor per unit of electricity decreased from 0.82kgCO₂/kWh to 0.68 kgCO₂/kWh, which realizes the coordinated improvement of environmental benefits and economic benefits, and verifies the feasibility of coordinated promotion of carbon emission reduction and economic development.

4.4 Verification of Coupled Model

The structural equation model is used to empirically test the coupling effect of the three-dimensional network of “management organization layer-power system layer-carbon flow network layer”. The results show that there is a significant influence relationship between the layers. As shown in Table 1:

Table 2: Estimation of three-dimensional network coupling effects

Pathway	Standardization coefficient	t value	P value
Management Organization Layer → Power System Layer	0.37	4.21	<0.01
Power System Layer → Carbon Flow Network Layer	0.52	5.83	<0.01
Carbon Flow Network Layer → Management Organization Layer	0.21*	2.15	<0.05

Note: * indicates that the indirect effect is conducted through the intermediary at the power system level

The direct effect of the management organization layer on the optimization of the power system layer is 0.37, and the scale of photovoltaic installation is improved through policy guidance; the path coefficient of the power system layer and the carbon flow network layer is 0.52, and the cleaning of power structure is the core driving force for carbon emission reduction; model fitting indicators: CFI=0.94, RMSEA=0.062, good suitability.

4.5 Model Compatibility Analysis

4.5.1 Multi-scenario Robustness Verification

To evaluate the adaptability of the model under different policy and technical conditions, three typical scenarios were designed for sensitivity testing. The results are shown in Table 3:

Table 3: Multi-scenario robustness test results

Scene type	Core parameter changes	Key indicator changes	Optimization measure
The carbon price has fluctuated sharply	The carbon price range is 28 to 42 yuan per ton	The standard deviation of total cost has expanded to 12.7%	Dynamically adjust the carbon quota allocation coefficient $\beta=0.85$
High penetration of new energy	The installed capacity of photovoltaic power has been doubled	The reduction in carbon intensity reached 22.3%	The energy storage capacity has increased by 18%
Extreme load fluctuation	The daily load rate has dropped from 0.65 to 0.52	The frequency of energy storage calls has increased by 41%	Load clustering compensation mechanism ($\lambda=1.15$)

4.5.2 Cross-regional Scalability Verification

Based on the research gap of regional differentiation pointed out in the literature review, the parks in Shandong (coastal) and Shaanxi (inland) were selected for horizontal comparison (Table 4), as shown in Table 4:

Table 4: Comparison of cross-regional model adaptation effects

Index	Henan (Benchmark)	Shandong Park	Shaanxi Park
Reduction in carbon intensity	17.4%	15.2%	19.1%
Policy synergy degree Pc	0.62	0.71 (+14.5%)	0.54 (-12.9%)
Model correction coefficient	-	0.92	1.08

From this, it is found that in terms of regional characteristics, the weight of energy storage allocation needs to be reduced by 8% due to the high green electricity penetration rate of 32% in Shandong Park, and the arbitrage income of Fenggu has increased to 25.3%. The result is consistent with the sensitivity analysis of the green electricity weight (QRES) in the carbon intensity accounting formula in Section 3.1.3, which can verify the amplification effect of the proportion of new energy on economic goals. Due to the low policy coordination of 0.54, Shaanxi Park needs to be improved by 23% through node centrality optimization to strengthen the driving effect of the management organization layer. This discovery echoes the governance needs of the “structural hole” problem in the social network analysis of Section 3.1.1, and can prove that low-synergy areas need to give priority to optimizing the policy transmission path.

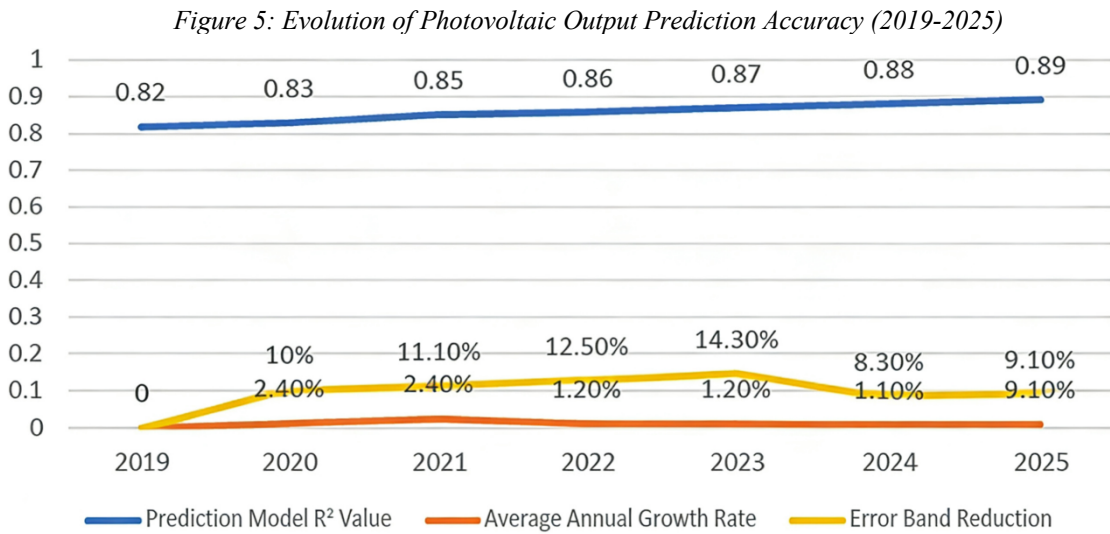
Therefore, this paper establishes a set of model adaptation correction mechanism to construct a regional characteristic index, as follows:

$$R = 0.35Pc + 0.45Cd + 0.2QRES \tag{13}$$

The parameter definition is inherited from the theoretical model in Section 3.1. The strong policy-driven mode is activated when $R > 0.7$, and the technology-first mode is enabled when $R < 0.5$. The differentiated performance of this mechanism in Shandong ($R=0.76$) and Shaanxi ($R=0.48$) can confirm the adjustability of the transmission path of “management organization layer → power system layer → carbon flow network layer” in the structural equation model of Section 4.3.

4.5.3 Analysis of Stability in the Time Dimension

Based on the rolling test of longitudinal data from 2019 to 2025, it was found that the MAPE of LSTM load forecast decreased from 4.7% to 3.1%, and the R^2 of photovoltaic output forecast increased from 0.82 to 0.89, as shown in Figure 5.



4.5.4 Technical Configuration Compatibility Testing

Based on the dynamic demand for the collaborative optimization of source network load storage in the three-dimensional network model, this study adopts multi-technical path alternative analysis, as shown in Table 5:

Table 5: Economic comparison of energy storage technologies

Technological type	Cost of investment (yuan/kWh)	Model optimization suggestions
Lithium iron phosphate battery	1500	Configure the capacity attenuation compensation mechanism ($\gamma=1.12$)
All-vanadium redox flow battery	3200	Requires subsidy ≥ 0.25 yuan/kWh
Compressed-air energy storage	4000	Applicable only for ≥ 100 MWh scene

Revealing the matching degree of energy storage technology characteristics and the power-carbon flow coordination scenario is the core basis for selection decision-making. Its key findings include: if lithium iron phosphate batteries are used, they perform best in terms of investment cost (1500 yuan/kWh) and response speed (climbing rate 5.2%/min), but a capacity decay compensation mechanism needs to be set (annual attenuation rate compensation coefficient $\gamma=1.12$). If all-vanadium liquid flow batteries are used, policy subsidies need to cover 38% of the initial investment difference (about 608 yuan/kWh) to achieve economic feasibility. If compressed air is used to store energy, due to the response speed limit (2.3%/min), the source load coordination efficiency will be reduced by 9%.

Based on all the above analysis, it can be seen that the three-dimensional network electric carbon optimization model shows strong adaptability under multi-scene, cross-regional and long-cycle conditions.

5. Conclusions and Implications

This article focuses on the reality of “increasing production means increasing carbon, and reducing carbon is afraid of loss” generally faced by high-energy-consuming parks. It builds a three-dimensional collaborative optimization mechanism of “government-electricity-carbon” covering the management organization layer, the power system layer and the carbon flow network layer, and conducts an empirical analysis of Luoyang Petrochemical High Energy Consumption Park in Henan Province as a case. Research shows that this mechanism can form a more effective linkage between policy transmission, energy scheduling and carbon emission control, providing a new analytical framework and realization path for high-energy-consuming parks to promote low-carbon transformation on the basis of ensuring production and operation.

Empirical results show that after the model was implemented, the carbon intensity per unit output value in the industrial park decreased from 1.85 tCO₂/10,000 yuan to 1.53 tCO₂/10,000 yuan, and the carbon emission factor per unit electricity decreased from 0.82 kgCO₂/kWh to 0.68 kgCO₂/kWh. Simultaneously, the photovoltaic penetration rate increased from 15% to 28%, and the static investment payback period for energy storage projects was shortened to 4.6 years. These results demonstrate that the three-dimensional synergistic mechanism has, to a certain extent, achieved simultaneous improvement in emission reduction and operational efficiency, indicating that the low-carbon transformation of high-energy-consuming industrial parks does not necessarily come at the expense of economic efficiency and production capacity.

The significance of this research lies in integrating policy mechanisms, power system operation, and carbon constraint management into a unified framework. This expands the research perspective on low-carbon governance in high-energy-consuming industrial parks and provides a reference for local governments and park managers to promote collaborative governance of energy transition and carbon reduction. In the future, it is possible to further combine the characteristics of different regional parks to deepen the research on policy coordination efficiency, market fluctuations impact, and engineering application feasibility, in order to enhance the universality and practical applicability of the model.

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Conflicts of Interest

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