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Research on Double-layer Optimal Dispatch and Carbon Reduction Potential of Electricity-gas Integrated Energy System Based on Carbon Trading Mechanism

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Abstract: This study develops a novel bi-level optimization framework incorporating carbon pricing mechanisms for integrated electricity-gas systems, enabling cost-effective low-carbon energy dispatch. The proposed approach employs a carbon emission flow model to quantify nodal carbon potentials and track emission pathways across energy networks. The optimization architecture consists of two interconnected layers: the upper layer minimizes power grid and natural gas network operational costs, while the lower layer optimizes energy procurement, equipment maintenance, and carbon trading expenditures. The alternating direction method of multipliers (ADMM) algorithm is implemented to solve this complex optimization problem. Case study results demonstrate the framework's effectiveness in balancing economic and environmental objectives: system-wide carbon emissions were reduced by 4.77 tCO_2, with power procurement costs decreasing by 6,533.45 yuan. Although natural gas expenses increased by 6,569.07 yuan due to the carbon trading mechanism, the overall framework achieved an improved equilibrium between operational efficiency and sustainable energy practices, providing valuable insights for low-carbon energy system optimization.

Keywords: Integrated energy system, Carbon trading mechanism, Two-layer optimal dispatch, Carbon emission flow, ADMM algorithm

1. Introduction

In the realm of carbon emission mitigation, China has introduced the “dual carbon objectives”. To achieve the“dual carbon goals”, it is crucial to establish an Integrated Energy System (IES) that combines energy production, supply, and marketing in order to increase energy utilization efficiency and lower carbon emissions.[1].

Some scholars have conducted in-depth research on carbon emission flow calculation. A study proposed the basic concept and calculation method of carbon emission flow [2]. Another study introduces the concept of ‘hub’ into carbon flow tracking and carbon accounting [3]. Moreover, a researcher established a carbon emission-energy flow model for multi-energy networks to track the sources of carbon emissions in various energy chains [4]. However, applying carbon emission flow models in IES still needs further exploration.

As demand-side resources continue to expand,research on tapping the potential of demand-side resources has gradually deepened. Researchers propose a strategy that balances demand response

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and operational economic benefits by providing an optimized bidding plan [5]. And a two-layer dispatch model is developed for regional IES, incorporating stakeholder games and flexible load management [6]. Similarly, a study has introduced incentive-based demand response to enhance the operational dispatch of virtual power plants [7]. These studies collectively advance the understanding of demand response through innovative modeling approaches. Nevertheless, they failed to incorporate the carbon trading mechanism for controlling the carbon emissions.

To sum up, this paper first introduces the carbon emission flow theory into the carbon trading mechanism. Secondly, it establishes an optimization model that includes an IES. A two-layer economic dispatch model for the electricity-gas connection is proposed. While the lower layer decreases energy acquisition costs, equipment maintenance costs, and carbon trading charges, the upper layer minimizes the operational costs of the natural gas network and electricity grid. The ideal operation plan is then solved using the ADMM algorithm. Lastly, an analysis of the carbon emissions and optimization findings is conducted.

2. Double-layer dispatching framework for electrical-gas systems

2.1. Integrated energy system architecture

This article examines a single IES system (Figure 1). The upper layer uses electricity and natural gas. Electric power has distribution networks and generators, and natural gas has wells and transmission pipelines. Wind turbines (WT), Gas turbines (GT), Energy storage system (ESS), Thermal energy storage (TES), and Heat pumps (HP) make up the lower layer, a single IES.

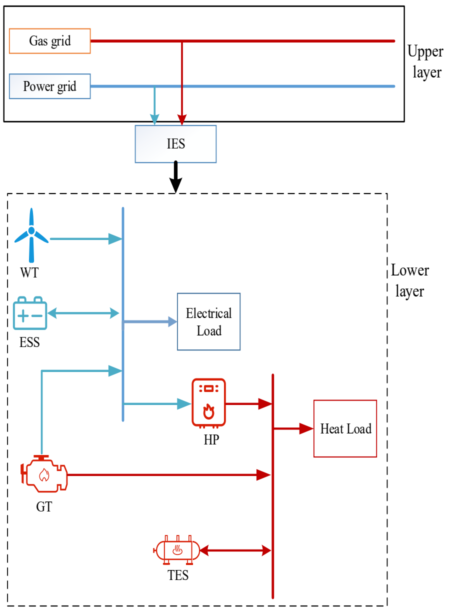

Figure 1: IES structure

2.2. Carbon accounting model based on carbon emission flow theory

The carbon emission flow model can be used to calculate carbon emissions in the production, transportation and consumption of energy, and assign carbon emission responsibilities to the consumer side of IES [8]. The node carbon potential quantifies the carbon emissions associated with unit power at the node, and its value is [9]:

$$e_n = \frac{\sum_{i\in\Omega_n^+} R_i}{\sum_{i\in\Omega_n^+} P_i} = \frac{\sum_{i\in\Omega_n^+} \rho_i \times P_i}{\sum_{i\in\Omega_n^+} P_i} \tag{1}$$

The mathematical formulation defines the following parameters: e_n represents the carbon potential at node n, while P_i denotes the active power flow transmitted from branch m to node i; The parameter ρ_i indicates the carbon flow intensity associated with branch m connected to node i. Furthermore, R_i characterizes the carbon emission flow through branch i. The collection of all incoming branches carrying power injection to node n is denoted as Ω_n^+.

A carbon emission flow model for the natural gas network is constructed utilizing power flow tracking [10]. The model is as follows:

$$e_{gas,n} = \frac{Q_{\varpi,n} e_{\varpi,n} + \sum_{i=1}^{I_{gas}} Q_{gas,i} \rho_{gas,i}}{Q_{\varpi,n} + \sum_{i=1}^{I_{gas}} Q_{gas,i}} \tag{2}$$

The mathematical formulation defines the following parameters for gas network analysis: $e_{gas,n}$ represents the carbon potential at gas node n, while $Q_{\varpi,n}$ denotes the flow rate from gas well w to node ϖ. The parameter $e_{\varpi,n}$ indicates the carbon emission intensity associated with gas well ϖ at node n. For pipeline analysis, $Q_{gas,i}$ characterizes the gas flow rate through pipelinei, and $\rho_{gas,i}$ represents the corresponding carbon potential of the gas flow. The cardinality of incoming gas flow branches at node n is denoted as I_{gas}.

2.3. Carbon trading mechanism modeling

Assessing the system's carbon emissions based on the carbon potential of each network node.

IES receives first carbon quotas from the government. When its carbon emissions are below the quota, extra quotas can be sold for profit. This yields the carbon trading model:

$$\begin{cases} D = \sum_{t=1}^{T}(e_n^t P_{grid,t} + e_{gas,n}^t V_{gas,t}) \\ Q = \sum_{t=1}^{T}(\alpha_1 P_{GT}^t + \alpha_2 H_{GT}^t) \\ f_{cet} = p_{cet}(D - Q) \end{cases} \tag{3}$$

In the formula, $P_{grid,t}$ and $V_{gas,t}$ is the amount of electricity and gas purchased by IES from the superior power grid at time t, P_{GT}^t and H_{GT}^t is the electric output and heat output of the gas turbine at time t, α_1 and α_2 is the carbon quota coefficient, D and Q is the actual carbon emissions and carbon quota of IES, p_{cet} is the unit price of carbon trading, and f_{cet} is the cost of carbon trading.

Furthermore, Green certificates can deduct carbon emissions based on their carbon emission reduction properties. From this, a model considering green certificate transactions is established:

$$\begin{cases} f_{gct} = p_{cet}(D - Q - D_e) \\ D_e = \alpha_3 e_{n,av} N_{gct} \end{cases} \tag{4}$$

In the formula, f_{gct} is the green certificate transaction cost, D_e is the carbon emission deduction amount of the green certificate, α_3 is the carbon emission deduction coefficient of the green certificate, $e_{n,av}$ is the average carbon potential of the distribution network, and N_{gct} is the number of green certificates required for assessment.

3. Double-layer optimal dispatch model of electrical-gas system

This article presents a two-tier financial dispatch model applied to the electric-gas network to comprehensively examine the carbon-free business opportunity of IES. The upper layer illustrates the

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economic dispatch model for the power delivery of the electric-gas framework, however the layer below signifies the financial dispatching system of a singular IES.

3.1. Upper-layer economic dispatch model

The upper-level model optimizes electricity-gas network operations, determining generator outputs, transmission flows, gas production, and pipeline capacities. It integrates a carbon flow system to calculate nodal carbon potentials, enabling system-wide emission tracking.

3.1.1. Objective function

The upper-level optimization model is designed to achieve minimum total energy supply expenditures, which primarily consist of fuel consumption costs for conventional thermal generation units and operational expenses related to natural gas production facilities. This cost-minimization objective function serves as the fundamental economic driver for the IES operational strategy.

$$\min F_1 = f_e + f_g \tag{5}$$

In the formula, f_e is the fuel cost of thermal power units and f_g is the cost of natural gas extraction. The calculation formula is as follows:

$$\begin{cases} f_e = \sum_{t=1}^{T} \sum_{i=1}^{I} \left(a_i P_{G,i,t}^2 + b_i P_{G,i,t} + c_i \right) \\ f_g = \sum_{t=1}^{T} \sum_{\varpi=1}^{J} \rho_{\varpi} Q_{\varpi,t} \end{cases} \tag{6}$$

In the formula, I is the number of thermal power units, J is the number of natural gas wells, $P_{G,i,t}$ is the power generation of the generator i at time t, a_i, b_i and c_i are respectively the power generation cost coefficient, ρ_{ϖ} are the extraction price of natural gas, and $Q_{\varpi,t}$ are the extraction volume of natural gas wells ϖ at time t.

3.1.2. Power grid and natural gas grid model constraints

The IES computes carbon emissions utilizing the carbon potential derived from the upper layer mode [11]. Natural gas network constraints include dual restrictions on gas well output, gas network pipeline constraints, and node pressure constraints, with reference to [12].

3.2. Lower-layer economic dispatch model

The IES calculates carbon emissions based on the carbon potential obtained from the upper-layer model, and uses the minimum sum of IES energy purchase, operation and maintenance, and carbon trading costs as the objective function to solve the optimal plan for purchasing electricity and gas from the upper layer.

3.2.1. Objective function

$$\min F_2 = f_{trans} + f_{op} + f_{cet} \tag{7}$$

In the formula, f_{trans} is the total capability cost, including the cost of electricity and gas purchase; f_{op} is the operation and maintenance cost of WT, GT, ESS and other equipment, and f_{cet} is the carbon trading cost, as mentioned above. Each cost calculation formula is as follows:

$$\begin{cases} f_{trans} = \sum_{t=1}^{T}\left(p_{grid,t}P_{grid,t} + p_{gas,t}V_{gas,t}\right) \\ f_{op} = \sum_{r\in S}\sum_{t=1}^{T} p_{r,op}\, P_{r,t} \end{cases} \tag{8}$$

In the formula, $p_{grid,t}$ and $p_{gas,t}$ are the electricity price and gas price at the time t, respectively, $P_{grid,t}$ and $V_{gas,t}$ are the electricity purchase power and gas purchase volume at the time t, respectively, S is a collection of WT, GT, HP, ESS and TES, $p_{r,op}$ and $P_{r,t}$ are the operation and maintenance cost coefficient and operating power of equipment r respectively.

3.2.2. Equipment model constraints

This paper considers the constraints of WT, GT, HP, ESS and TES, with reference to [13].

3.2.3. Model solving

This article employs the ADMM method to address this issue. Consult reference [14] for pertinent formulas. The procedural steps are as follows:

- Initialize variables. Including the interaction variables $P_{grid,t}$ and $V_{gas,t}$ between the upper and lower layers; Lagrange multipliers λ_p^k and λ_g^k; setting the penalty parameter ρ, the convergence threshold ε_{tol} and the maximum number of iterations M. Set the number of iterations k=0.
- Set the number of iterations $k \to k+1$. Fix the lower-layer variables $P_{grid,t}^{k,l}$ and $V_{gas,t}^{k,l}$, perform optimal scheduling of the upper-layer electrical-gas network, and update $P_{grid,t}^{k,u}$ and $V_{gas,t}^{k,u}$.
- Compute the carbon potential of each node within the network according to the optimization outcomes of the upper layer system and transmit this information to the lower layer.
- Fix the upper-layer variables $P_{grid,t}^{k,u}$ and $V_{gas,t}^{k,u}$, perform optimal scheduling of the lower-layer electrical-gas network, and update $P_{grid,t}^{k,l}$ and $V_{gas,t}^{k,l}$.
- Update Lagrange multipliers λ_p^k and λ_g^k.
- Calculate the residuals ε_p and ε_g of the energy purchased by the upper and lower layers.
- Judgment of termination conditions. Take $\varepsilon = \max\left(\varepsilon_p, \varepsilon_g\right)$, if $\varepsilon < \varepsilon_{tol}$, stop iteration and output the running result. Otherwise return to step 2).

This article calls the commercial solver CPLEX 12.8 and YALMIP toolbox in Matlab 2021a for solution.

4. Example analysis

4.1. Basic data

This paper uses a 5-node power grid, a 6-node natural gas grid and an IES for example analysis. The structure diagram of the system is shown in the figure 2. G is the generator unit, GW is the natural gas well, and IES is the integrated energy system.

The generator set parameters are shown in Table 1. Some equipment parameters of IES refer to the literature [15]. Set the penalty parameter $\rho = 1.08$, the convergence threshold ε_{tol}=0.05MW, and the maximum number of iterations M=100. Set the scheduling period to 24h, conduct a simulation with

1h as a step, and set up two scenarios to analyze the economy and low-carbonity of the model proposed in this article:

Scenario 1: Optimal dual-layer dispatch of the electricity-gas system excluding the carbon trading mechanism

Scenario 2: Optimal dual-layer dispatch of the electricity-gas system using a carbon trading mechanism

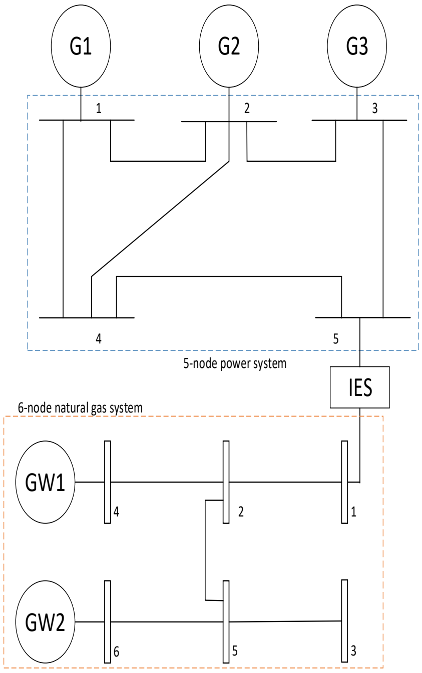


Figure 2: Structure of system

Table 1: Generator set parameters

Generator set	Installed capacity/MW	ai	bi	ci	Carbon emission coefficient/(tCO2/MWh)
G1	3	0.014	175	100	0.95
G2	3	0.023	175	60	0.95
G3	3	0.069	175	50	0.92

4.2. Result analysis

The outcomes of the dispatching process across various scenarios are presented in Table 2:

Table 2: Dispatching results under different scenarios

Scenario	Total cost of upper-layer system	Lower layer system				
		Total cost/yuan	Power purchase cost/yuan	Gas purchase cost/yuan	Carbon trading cost/yuan	Carbon emissions/t
1	61690.20	59973.48	25965.21	34004.17		43.63
2	63627.46	63184.05	19431.76	40573.24	3174.76	38.86

The table indicates that in scenario 1, the system purchases more electricity due to the absence of carbon trading, resulting in higher electricity acquisition costs compared to scenario 2. In Scenario 2, influenced by the carbon trading mechanism, the expense for electricity procurement decreases by

6,533.45 yuan relative to Scenario 1, however the expenditure for gas procurement rises by 6,569.07 yuan. This indicates that the carbon trading mechanism leads to a decrease in the procurement of energy with elevated carbon emissions, favoring the utilization of gas turbines to mitigate carbon output. The carbon emissions of the IES are diminished by 4.77 tCO_2, demonstrating the efficacy of the carbon trading mechanism in facilitating low-carbon dispatch. The aforementioned results indicate that the implementation of the carbon trading mechanism has influenced the energy procurement strategy to some degree, prompting the system to change the ratio of electricity and gas purchases to enhance economic efficiency and reduce carbon emissions.

Figure 3 presents the carbon potential distribution across the IES nodal points. Analysis of the temporal variation reveals a substantial increase in carbon potential at the IES-containing node during the morning period (09:00-12:00), followed by maintenance of relatively high values throughout the afternoon and evening hours (12:00-21:00). This is because the electricity consumption of IES rises to its peak, and the system's power purchase increases, causing the output of generator units to rise. Since the carbon emission intensity of generator units is relatively high, the carbon emission increases accordingly. From 21:00 to 24:00, due to the reduction in the system's load, the output of generator units decreases, and the carbon potential drops to the lowest level. This shows that the carbon market mechanism guides low-carbon dispatch and promotes energy use.

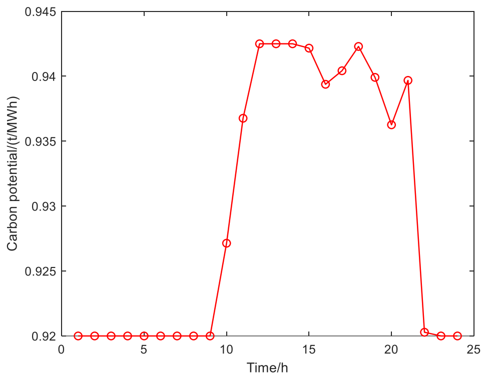


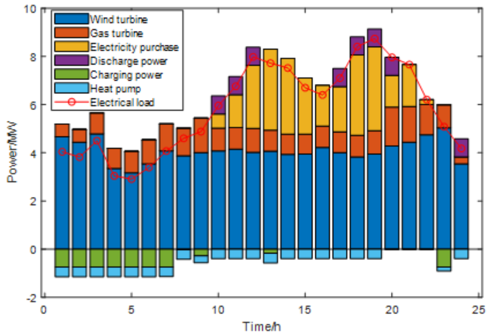
Figure 3: Carbon potential of IES node

The electric power balance diagram of IES under scenario 1 is shown in Figure 4(a). During the period from 01:00 to 08:00, the system uses WT and GT as the main energy sources, and ESS stores excess electric energy for backup. The peak periods of electricity consumption are 10:00-12:00 and 17:00-21:00, and ESS releases the stored electric energy. At the same time, the system purchases power from the superior power grid to meet the needs of the electrical load. In addition, HP is put into use during most of the day to convert excess electrical energy into thermal energy to meet the needs of the heat load.

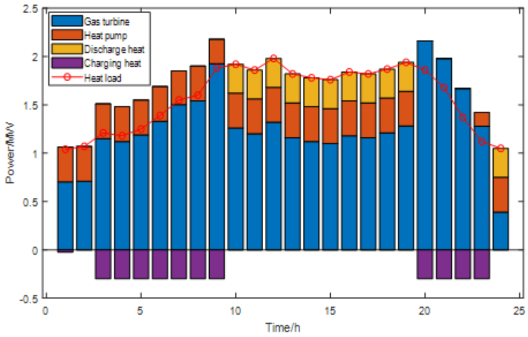
The thermal power balance diagram of IES under scenario 1 is shown in Figure 4(b). The system primarily uses GT for power, with HP converting excess electricity to heat, meeting demand and boosting renewables. TES charges during off-peak (01:00-09:00, 20:00-23:00) and discharges at peak hours (10:00-19:00), balancing thermal loads.

IES's scenario 2 electric power balancing diagram is presented in Figure 4(c). Compared to scenario 1, HP output decreases during peak power usage and GT output increases. The implementation of carbon emission trading policies promotes a shift toward cleaner energy sources by incentivizing the utilization of natural gas, characterized by its relatively lower carbon footprint, for meeting energy requirements. This market-based mechanism effectively reduces greenhouse gas emissions through economic incentives that encourage the selection of more environmentally sustainable fuel options.The system's power purchase is lower than in Scenario 1 since HP no longer adds electrical load during peak power usage.

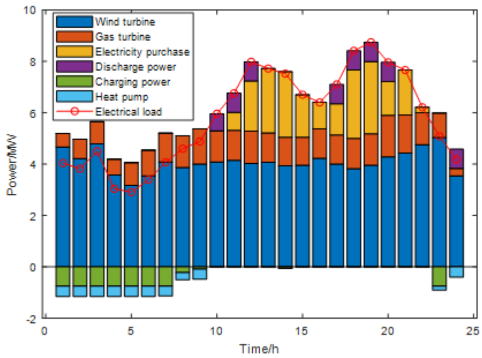
Figure 4(d) illustrates the thermal energy equilibrium distribution within the IES for scenario 2. Analysis of the heating load profile reveals that GT and TES serve as primary heat sources during peak demand periods. In contrast to scenario 1, HP demonstrate substantially lower operational output during high-demand intervals, with their utilization predominantly shifted to off-peak periods. This operational pattern modification indicates that the implementation of carbon emission trading policies has effectively decreased the system's reliance on electrical energy while promoting increased utilization of natural gas as an alternative energy source.



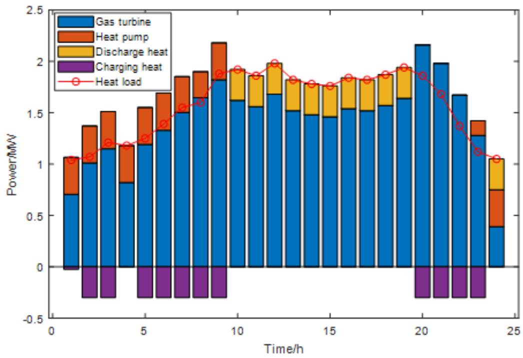
a. Electric power balance of IES under scenario 1



b. Thermal power balance of IES under scenario 1



c. Electric power balance of IES under scenario 2



d. Thermal power balance of IES under scenario 2

Figure 4: Electrical/thermal power balance of IES in different scenarios

Table 3 shows IES's heat-generating equipment output under different conditions. After considering the carbon trading mechanism, Scenario 2 HP output drops 3.60MWh but GT output rises 3.60MWh. To limit carbon emissions, the system uses GT instead of HP during high heat load periods due to carbon trading prices. Due to HP's limited peak-shaving effect, the system's power purchase is also reduced, lowering its dependency on high-carbon electricity.

Table 3: Output of heat-generating equipment in different scenarios

Scenario	HP/MWh	GT/MWh
1	7.23	30.64
2	3.63	34.24

The convergence process of energy purchase error in the electricity-gas network is shown in Figure 5. During the iteration process, the residual oscillation attenuated, and finally converged after

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46 iterations, at which timeε=0.037MW. The ADMM algorithm converges within 50 iterations, indicating that this algorithm has good results in solving double-layer optimization problems.

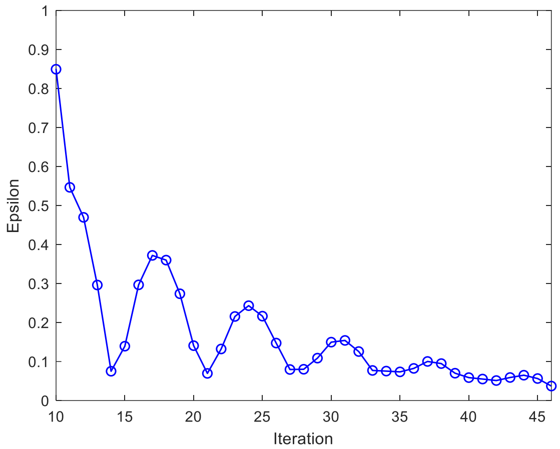

Figure 5: The convergence process of energy purchase error

5. Conclusion

In summary, this study investigates the integrated electricity-gas energy system under the carbon trading mechanism, producing noteworthy results. A model for tracking carbon emission flows has been developed, enabling accurate quantification of emissions across energy generation, transmission, and utilization phases. This approach not only assigns emission accountability to end-users but also creates a comprehensive assessment framework for system-wide carbon emissions.The carbon trading mechanism effectively reduces emissions by 4.77 tons of CO_2, promoting a low-carbon dispatch model. It also optimizes the energy procurement structure, reducing electricity purchase costs by 6533.45 yuan while increasing gas costs by 6569.07 yuan, balancing economic and low-carbon goals. The ADMM algorithm solves the two-layer optimization problem efficiently, converging within 50 iterations. However, the model focuses on a single IES and overlooks uncertainties like renewable energy fluctuations and carbon price changes. Future research should expand to multiple IESs, refine equipment models, and incorporate stochastic or robust optimization methods to enhance practicality and accuracy. This study offers valuable insights for advancing low-carbon energy systems.

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