

Source-Load Interactive Low-Carbon Scheduling of Integrated Energy Systems Under CET-CCER Market Mechanisms

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ABSTRACT

Accurate carbon accounting and demand-side coordination are essential for the low-carbon operation of integrated energy systems (IESs) under carbon market mechanisms. Existing studies have mainly focused on source-side carbon allocation or price-based demand response, while the coordination among carbon tracing, carbon markets, and load-side carbon responsibility remains insufficient. This paper proposes a source-load interactive low-carbon scheduling framework for IESs under joint carbon emission trading (CET) and Chinese Certified Emission Reduction (CCER) mechanisms. A full-chain carbon tracing method based on carbon emission flow theory is first used to identify carbon responsibility across electricity, gas, heat, and energy conversion processes. A spatial dynamic carbon emission factor is then introduced as the carbon signal for low-carbon demand response (LCDR). On this basis, renewable generation and LCDR-induced emission reductions are integrated into a unified CET-CCER incentive framework, and a bi-level scheduling model is developed to coordinate the integrated energy service provider and energy consumers. Case results under 40%, 65%, and 90% wind penetration scenarios show that the proposed framework reduces operating cost and carbon emissions while improving renewable energy accommodation. The role of LCDR becomes more significant under high renewable penetration, where carbon-oriented load shifting mitigates wind curtailment and reduces reliance on thermal generation.

KEYWORDS

Integrated energy system; Carbon emission flow; Spatial dynamic carbon emission factor; Low-carbon demand response; CCER; Bi-level scheduling

1 Introduction

Achieving carbon peaking and carbon neutrality has accelerated the transformation of integrated energy systems (IESs). Electricity-centered multi-energy systems remain important sources of carbon emissions, and their low-carbon operation requires both accurate carbon responsibility allocation and coordinated scheduling of flexible resources [1-2]. With the development of China's carbon emission trading (CET) market and the restarting of the Chinese Certified Emission Reduction (CCER) mechanism, carbon assets and operational carbon reduction can be more closely connected with system dispatch. Carbon emission flow (CEF) theory provides a useful basis for tracing carbon responsibility from generation to consumption. Recent studies have extended CEF-based methods to integrated electricity-gas-heat systems, carbon capture processes, and multi-energy hubs [1-2]. In parallel, demand response and carbon trading have been introduced into low-carbon IES optimization [3-8]. However, three gaps remain. First, many studies still emphasize source-side carbon allocation, while full-chain carbon responsibility across electricity, gas, heat, and conversion devices is not sufficiently linked with operational decisions. Second, demand response is usually driven by electricity prices or fixed incentives, rather than by the real-time carbon characteristics of delivered energy. Third, the interaction among carbon tracing, CET-CCER incentives, and demand-side low-carbon response has not been systematically incorporated into a unified source-load scheduling framework. To address these gaps, this paper develops a source-load interactive low-carbon scheduling framework for IESs under CET-CCER market mechanisms. The main contributions are as follows. First, a full-chain carbon tracing framework is constructed to describe carbon responsibility transfer across electricity, gas, heat, and energy hub conversion processes. Second, a spatial dynamic carbon emission factor is introduced to convert carbon tracing results into a demand-side carbon signal, reducing locational bias and supporting LCDR. Third, renewable-generation-related emission reductions and LCDR-induced emission reductions are incorporated into a unified CET-CCER incentive mechanism. Fourth, a bi-level scheduling model is formulated to coordinate system dispatch and user response under carbon signals. The remainder of this paper is organized as follows. Section 2 presents the carbon tracing framework and spatial dynamic carbon emission factor. Section 3 develops the CET-CCER mechanism and source-load interaction process. Section 4 formulates the reduced bi-level scheduling model. Section 5 reports the case study and discussion. Section 6 concludes the paper.

2 Carbon Tracing Framework and Dynamic Carbon Signal

2.1 Full-chain Carbon Tracing Logic

The proposed carbon tracing framework links source-side emissions, network carbon transfer, energy conversion, and

load-side consumption. It uses three indicators: carbon emission intensity, carbon emission flow, and carbon emission factor. Carbon emission intensity describes direct emissions from energy production units; carbon emission flow describes how carbon responsibility is transmitted through electricity, gas, heat, and conversion networks; and the load-side carbon emission factor reflects the carbon responsibility associated with final energy consumption. This framework converts physical energy flows into carbon responsibility flows and provides the accounting basis for carbon-market-oriented scheduling.

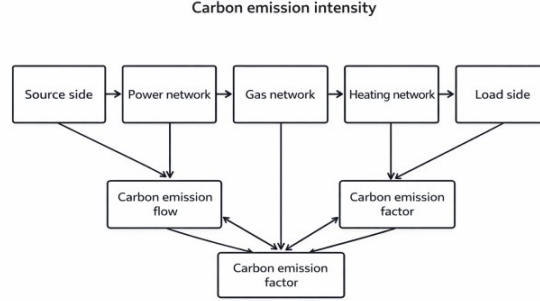


Figure 1 Full-chain carbon tracing framework of the integrated energy system

2.2 Carbon Transfer Across Electricity, Gas, Heat, and Energy Hubs

In the electricity network, nodal carbon potential is obtained according to the proportional sharing principle of CEF theory. Source-side carbon intensity is propagated through power flows and allocated to downstream loads. The same tracing logic is extended to the natural gas and heating networks, where carbon responsibility is transmitted according to gas flows, heat flows, and the corresponding network balance relationships. In energy hubs, devices such as CHP units, gas boilers, and power-to-gas facilities redistribute carbon responsibility among different energy carriers according to carbon conservation and conversion efficiency. Therefore, the carbon responsibility of each output energy carrier can be consistently traced back to its input energy sources.

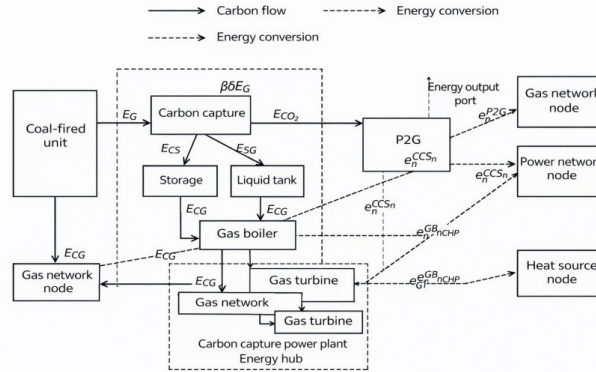


Figure 2 Carbon transfer diagram of the energy hub

2.3 Spatial Dynamic Carbon Emission Factor

Direct use of nodal carbon potential may cause locational inequity because users located near renewable units may obtain lower carbon responsibility than users located elsewhere. To reduce this bias, this paper introduces a load-weighted spatial averaging method. The spatial dynamic carbon emission factor of load type i at time t is expressed as:

$$e_{i,t} = \frac{\sum_{m \in \Omega_i} L_{m,t} e_{m,t}}{\sum_{m \in \Omega_i} L_{m,t}} \quad (1)$$

where $e_{m,t}$ is the nodal carbon potential, $L_{m,t}$ is the load at node m , and Ω_i is the set of nodes belonging to load type i . This factor reflects the time-varying carbon intensity of delivered energy and serves as the key signal for LCDR. When the factor is low, users are encouraged to shift flexible demand to that period; when it is high, users are encouraged to reduce or postpone consumption.

3 CET-CCER Coupled Mechanism and Source-Load Interaction

3.1 Joint CET-CCER Mechanism

The CET market constrains emissions through allowance trading, while the CCER mechanism provides additional value for certified emission reductions. In the proposed framework, both renewable generation and LCDR are allowed to generate carbon reduction benefits. This design extends CCER value creation from source-side renewable projects to coordinated source-load low-carbon actions. The carbon tracing model provides the accounting basis, while the spatial

dynamic carbon emission factor provides the operational signal for demand-side participation.

For wind power, certified emission reductions are calculated using the regional grid baseline emission factor:

$$e_{CM} = 0.75e_{OM} + 0.25e_{BM} R_{w,t}^{CCER} = P_{w,t} e_{CM} \quad (2)$$

For LCDR, emission reductions are measured by comparing carbon responsibility before and after load shifting:

$$R_{L,t}^{CCER} = \sum_i e_{i,t} (L_{i,t}^0 - L_{i,t}^{DR}) \quad (3)$$

where $R_{w,t}^{CCER}$ and $R_{L,t}^{CCER}$ denote CCER benefits from wind generation and LCDR, respectively. Equations (2) and (3) preserve the core carbon-market logic while avoiding excessive formula expansion.

3.2 Source-load Interactive Scheduling Process

The integrated energy service provider first optimizes system dispatch and calculates spatial dynamic carbon emission factors. These carbon signals are then transmitted to consumers, who adjust electricity, heat, and gas demand through LCDR. The updated load profile is fed back to the upper-level dispatch model. Through this iterative process, the system forms a closed loop among carbon tracing, carbon market incentives, and demand-side response.

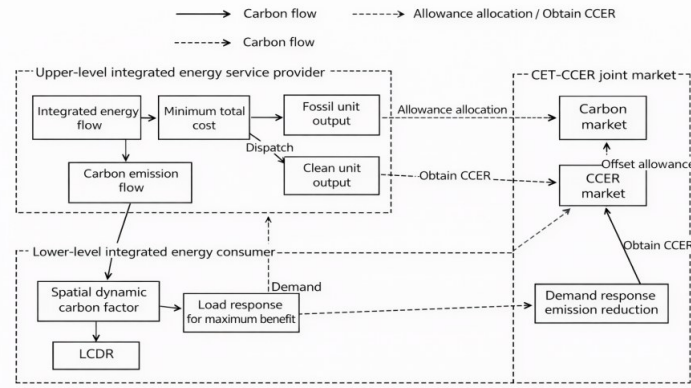


Figure 3 Source-load interactive low-carbon scheduling framework

Compared with conventional source-side scheduling, the proposed framework transforms passive load into an active low-carbon resource. It not only improves renewable energy accommodation but also enables users to share carbon reduction benefits through CCER-related incentives.

4 Bi-level Low-Carbon Scheduling Model

The scheduling model includes an upper level for the integrated energy service provider and a lower level for energy consumers. To reduce the length of the paper and avoid excessive formula occupation, only the core objective functions and key constraint groups are retained here; detailed device and network constraints can be provided in an appendix if required by the journal.

4.1 Upper-level Model

The upper-level model minimizes total system operating cost by optimizing thermal units, carbon capture facilities, wind power, CHP units, gas boilers, power-to-gas devices, and energy purchases. The compact objective function is:

$$\min C_{up} = C_{en} + C_{om} + C_{su} + C_{car} + C_{cur} - B_w^{CCER} \quad (4)$$

where C_{en} , C_{om} , C_{su} , C_{car} , and C_{cur} denote energy purchase cost, operation and maintenance cost, start-up/shut-down cost, carbon-related cost, and wind curtailment penalty, respectively; B_w^{CCER} is the CCER revenue from wind power. The upper-level model is subject to electricity, heat, and gas balance constraints; output and ramping limits; minimum up/down time constraints; carbon capture operation constraints; network flow limits; spinning reserve constraints; and CCER offset limits. These constraints ensure secure operation while allowing carbon-market incentives to influence dispatch decisions.

4.2 Lower-level Model

The lower-level model describes consumer response to the spatial dynamic carbon emission factor and carbon incentive signals. Users minimize their net energy cost after considering CCER benefits from LCDR:

$$\min C_{low} = C_{user} - B_L^{CCER} \quad (5)$$

The lower-level model includes load shifting balance constraints, transfer capacity constraints, and user satisfaction constraints. These constraints ensure that response behavior remains feasible and does not excessively reduce user comfort. Through LCDR, part of the load is shifted from high-carbon periods to low-carbon periods, thereby improving the temporal matching between renewable generation and demand.

4.3 Solution Method

The bi-level scheduling problem is transformed into a mixed-integer linear programming (MILP) problem through standard linearization of nonlinear terms. The upper and lower levels are solved iteratively. In each iteration, the upper level updates dispatch results and spatial dynamic carbon emission factors, while the lower level updates flexible demand according to carbon signals. The process stops when the change in load profile and total cost is below the convergence tolerance. The final MILP model is solved using Gurobi.

5 Case Study and Discussion

5.1 Case Description

The test system consists of an IEEE-30 bus electricity network, a 6-node heating network, and a 6-node natural gas network. It includes conventional thermal units, a carbon capture power plant, wind power, CHP units, a gas boiler, and a power-to-gas facility. Three wind penetration scenarios are considered: 40%, 65%, and 90%. Under each scenario, three strategies are compared: S1, CET only; S2, CET-CCER; and S3, CET-CCER with LCDR. The comparison evaluates the economic, carbon reduction, and renewable accommodation effects of the proposed framework.

5.2 Economic and Carbon Performance

To reduce table length, Table 1 reports the two most important indicators: total operating cost and carbon emissions. The original cost decomposition can be moved to an appendix if the journal allows supplementary material.

Table 1 Total cost and carbon emissions under different scenarios

Wind penetration	Strategy	Total cost (10 ⁴ CNY)	Carbon emissions
40%	S1: CET	268.9	3584
40%	S2: CET-CCER	263.6	3542
40%	S3: CET-CCER+LCDR	259.0	3455
65%	S1: CET	270.0	3012
65%	S2: CET-CCER	260.4	3006
65%	S3: CET-CCER+LCDR	253.7	2874
90%	S1: CET	285.8	2720
90%	S2: CET-CCER	276.7	2714
90%	S3: CET-CCER+LCDR	268.9	2593

The results show that the CCER mechanism reduces total cost in all wind scenarios because renewable generation obtains additional carbon-related revenue. Compared with S1, S2 reduces total cost by 1.97%, 3.56%, and 3.18% under 40%, 65%, and 90% wind penetration, respectively. After LCDR is introduced, S3 achieves further cost reductions because users shift part of their demand toward low-carbon periods, reducing thermal generation and carbon-related cost. Compared with S1, S3 reduces total cost by 3.68%, 6.04%, and 5.91%, respectively.

Carbon emissions also decline as wind penetration increases. However, the carbon reduction effect differs across strategies. S2 mainly improves the economic value of renewable generation, while its direct emission reduction effect is limited. In contrast, S3 achieves the lowest emissions in all scenarios because LCDR improves the temporal matching between renewable output and demand. Under 90% wind penetration, S3 reduces emissions by 127 units compared with S1, indicating that demand-side flexibility becomes more valuable when renewable fluctuation is stronger.

5.3 Carbon Signal and LCDR Performance

The spatial dynamic carbon emission factor is the key link between carbon accounting and demand response. Table 2 shows that the electricity system has a much larger peak-valley difference than the heating and natural gas systems, indicating stronger temporal variation and greater response potential.

Table 2 Peak-valley differences of dynamic carbon emission factors

System	Peak-valley difference (%)
Power system	70.93
Heating system	3.61
Natural gas system	1.66

Under low wind penetration, thermal units remain the dominant power supply source, and the temporal variation of carbon factors is relatively limited. In this case, LCDR mainly smooths the load profile and reduces peak regulation pressure. Under high wind penetration, renewable output causes stronger variation in carbon factors. Users are therefore guided to increase demand during low-carbon periods with abundant wind power and reduce demand during high-carbon periods. This shift improves wind power accommodation, reduces wind curtailment, and lowers dependence on carbon-intensive thermal generation.

5.4 Discussion

The case results confirm that the proposed framework improves economic performance, reduces emissions, and enhances renewable energy accommodation. The spatial dynamic carbon emission factor plays a central role because it transforms carbon tracing results into a practical operational signal for users. Compared with conventional price-based

demand response, carbon-oriented response better reflects the actual environmental impact of consumption at different times. The results also indicate that CCER incentives and LCDR are complementary: CCER improves the economic value of renewable generation, while LCDR increases the system's ability to consume renewable energy. Nevertheless, the current model does not fully consider renewable uncertainty, heterogeneous consumer behavior, or detailed verification rules for demand-side CCER certification. These issues should be further addressed before large-scale practical implementation.

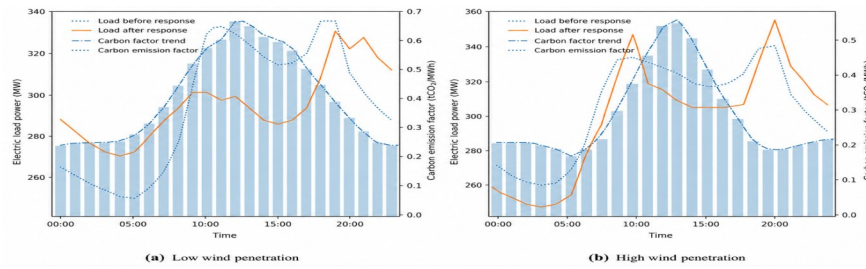


Figure 4 LCDR of electric load

6 Conclusion

This paper proposes a source-load interactive low-carbon scheduling framework for integrated energy systems under CET-CCER market mechanisms. A full-chain carbon tracing method based on CEF theory is used to quantify carbon responsibility across electricity, gas, heat, and energy conversion processes. A spatial dynamic carbon emission factor is introduced to support demand-side carbon responsibility allocation and LCDR. Based on this carbon signal, renewable-generation-related and LCDR-induced emission reductions are integrated into a unified CET-CCER incentive framework, and a bi-level scheduling model is developed to coordinate source-side dispatch and user-side response. The case study shows that CCER participation reduces system operating cost by converting renewable generation into carbon assets. When LCDR is further introduced, both operating cost and carbon emissions decline, and renewable energy accommodation improves. The effect becomes more significant under high wind penetration because stronger temporal variation in carbon factors creates greater value for carbon-oriented load shifting. Therefore, the proposed framework provides a feasible pathway for linking carbon tracing, carbon markets, and demand-side flexibility in low-carbon IES operation. Future research may focus on stochastic renewable output, heterogeneous user response behavior, dynamic carbon market prices, and practical measurement, reporting, and verification rules for demand-side CCER certification.

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