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Research on Multi-Level Low-Carbon Optimal Operation of Integrated Energy Systems Driven by Dynamic Carbon Entropy

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Abstract

To address the challenges posed by the unclear spatiotemporal distribution of carbon emissions in integrated energy systems and the difficulties in multi-level coordinated carbon reduction, this project proposes dynamic carbon entropy theory and constructs a precise carbon emission tracking method spanning from source to load side. By establishing a two-level optimization model based on carbon entropy and a dynamic carbon pricing mechanism, the project enables coordinated low-carbon operation across two key hierarchical levels—namely the "transmission–region" and "region–user" levels. The research findings provide novel theoretical tools and technical pathways for constructing a low-carbon optimization paradigm of cross-level coordinated integrated energy systems.

I. Background

This project aims to construct a precise carbon emission quantification method centered on the dynamic carbon entropy theory, breakthrough the bottlenecks of multi-level coordinated carbon reduction in integrated energy systems, and enable the overall low-carbon, economical, and efficient operation of the system by establishing a cross-level coordinated optimization mechanism.

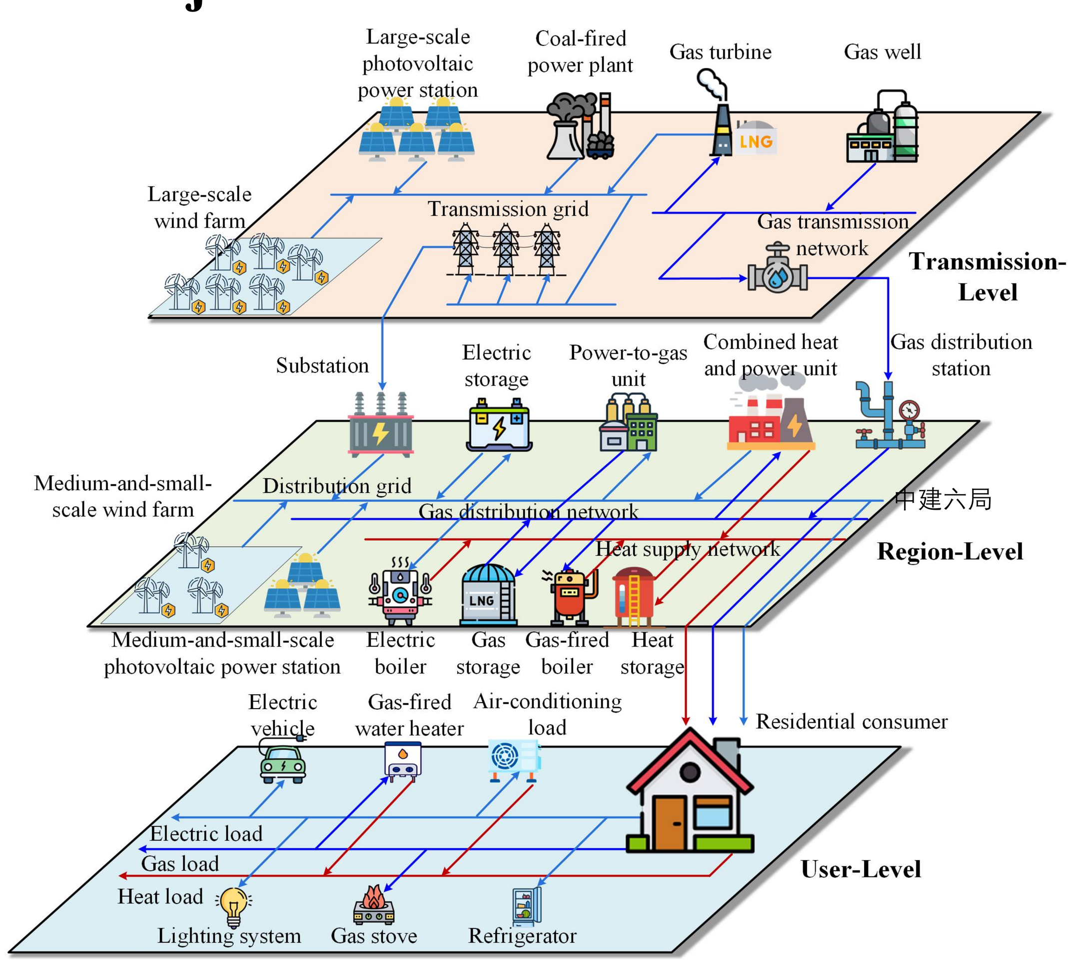
① Establish a dynamic carbon entropy theory framework: construct a precise carbon emission quantification method centered on the dynamic carbon entropy theory to reveal the spatiotemporal transmission patterns of carbon emissions within coupled multi-energy flow systems.

② Breakthrough the bottlenecks of multi-level coordinated carbon reduction: design a cross-level coordinated optimization mechanism to address the challenges of achieving coordinated low-carbon operation across transmission-level, region-level, and user-level systems.

③ Realize system multi-dimensional coordinated optimization: promote the integrated energy system to realize the unified improvement of low-carbon, economy and operational efficiency through carbon entropy guided optimal scheduling.

④ Form a replicable technical path: establish a complete theoretical and methodological system to provide innovative solutions and technical support for the deep decarbonization of integrated energy systems.

II. Project Introduction



■ Difficulty in Precisely Quantifying Multi-source Systems' Carbon Emissions

The multi-source characteristics of integrated energy systems and the complexity of energy conversion and consumption processes lead to significant differences in carbon emission factors across production, conversion and consumption stages.

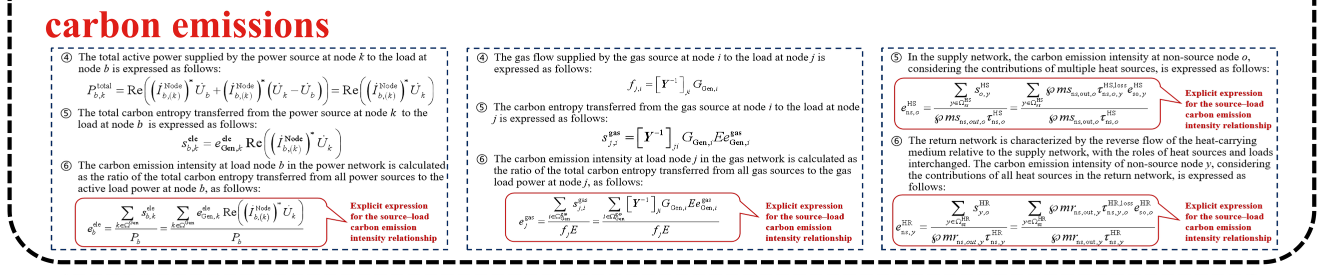
■ Difficulty in Fully Tapping Low-carbon Potential at Multi-levels

Imposing carbon emission costs only on transmission-level integrated energy systems can hardly drive regional-level integrated energy systems to actively adjust their energy demand, which prevents their low-carbon potential from being fully tapped and thus fails to effectively reduce the overall carbon emissions of the system.

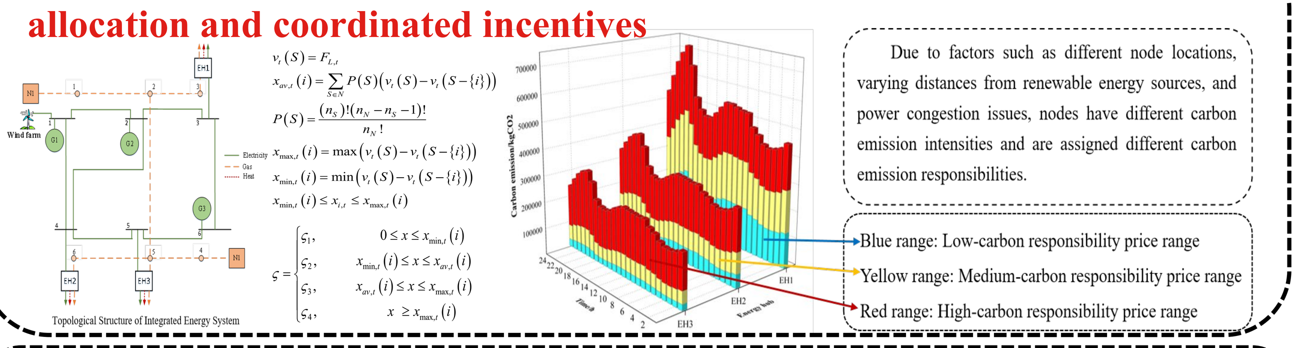
■ Difficulty in Precisely Guiding User Demand Response

Research on the construction of carbon price signal models is not sufficiently in-depth in terms of leveraging precise carbon price signals to guide users to actively participate in low-carbon demand response, drive changes in users' energy-use habits, and tap the low-carbon potential of multi-energy users.

Key Issues: Difficulty in dynamic tracking and precise quantification of carbon emissions

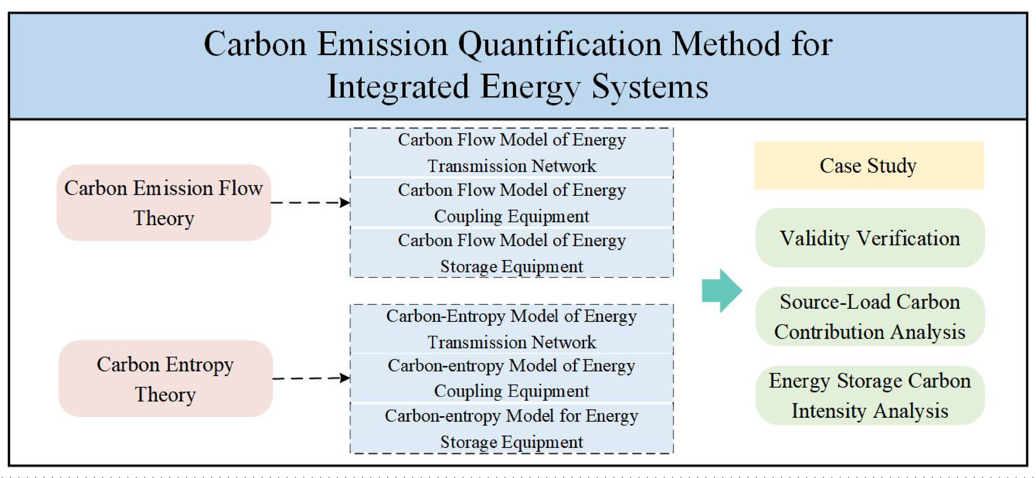


Key Issues: Difficulty in cross-level carbon emission responsibility allocation and coordinated incentives

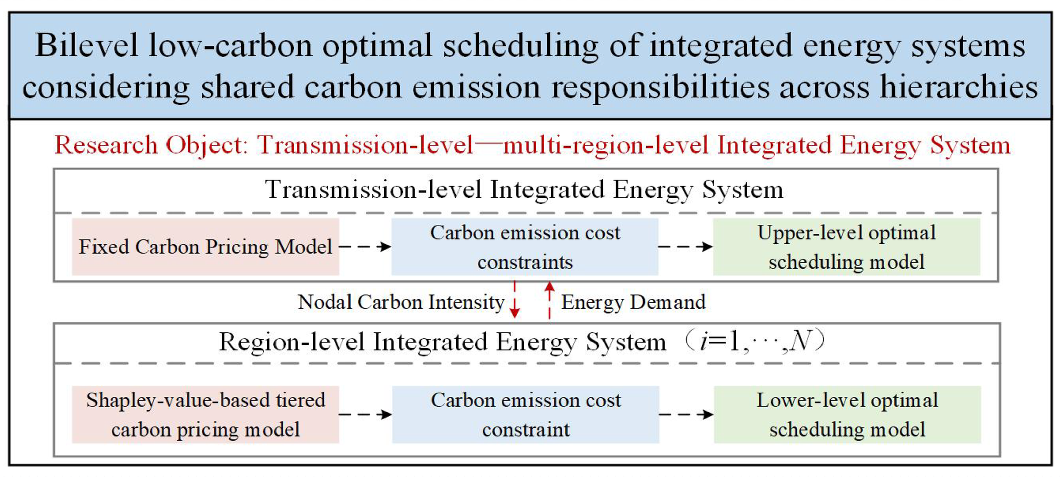


Key Issues: Difficulty in Precise Guidance of User-side Low-carbon Demand Response

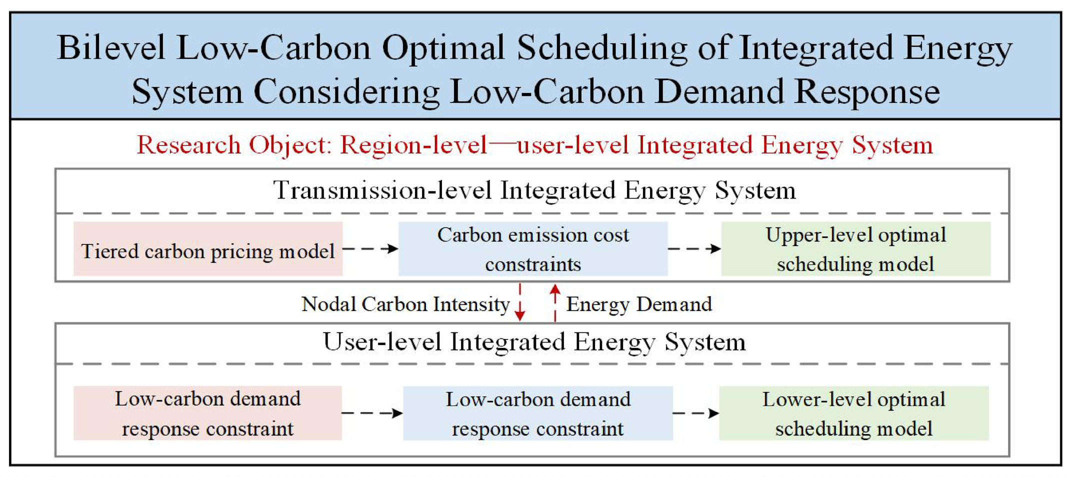
Integrated Electricity-Carbon Price	Integrated gas-carbon price	Integrated heat-carbon price
$\rho_{ec,sell,c,t} = \rho_{ec}^{ESP} + \xi_{co_2} e_{c,t}^{ele}$	$\rho_{ge,sell,u,t} = \rho_{ge}^{ESP} + \xi_{co_2} e_{u,t}^{gas}$	$\rho_{hc,sell,o,t} = \rho_{hc}^{ESP} + \xi_{co_2} e_{o,t}^{HS}$



Theoretical support



Further exploration



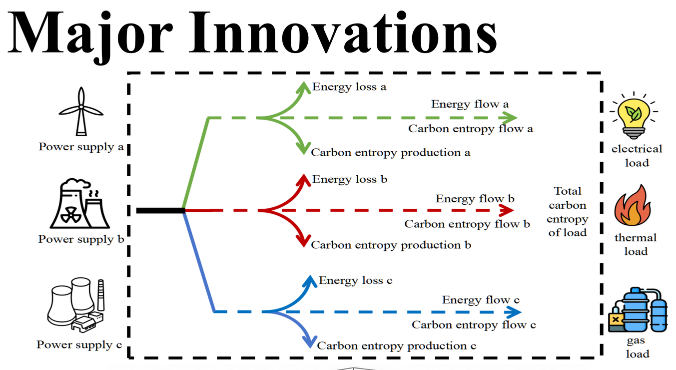
III. Research Progress and Major Innovations

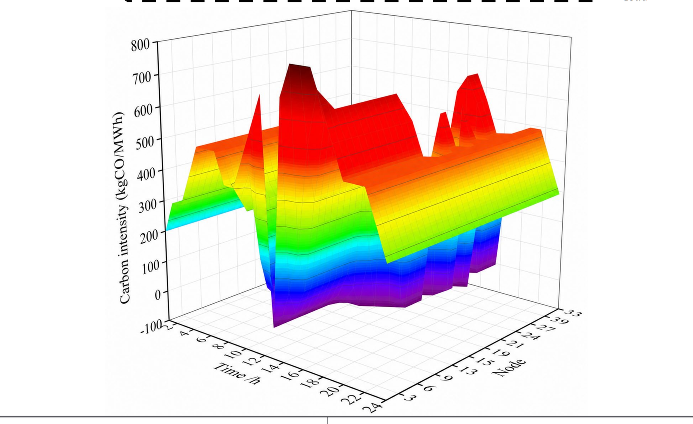
① Establish a dynamic carbon entropy theory framework

② Breakthrough the bottlenecks of multi-level coordinated carbon reduction

③ Realize system multi-dimensional coordinated optimization

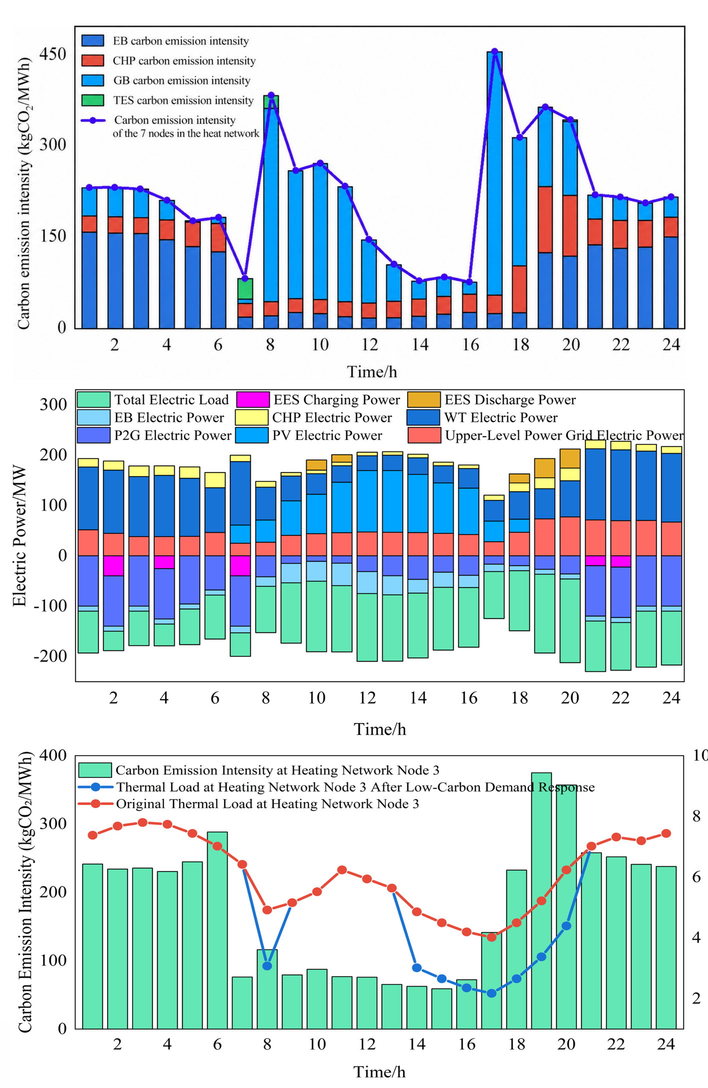
④ Form a replicable technical path





case	Upper-level costs (×10⁴ RMB) Power generation cost	Mining cost	Operation and maintenance cost	Carbon emission cost	Lower-level costs (×10⁴ RMB) Electricity purchase cost	Gas purchase cost	Operation and maintenance cost	Carbon emission cost	Carbon emissions (tCO₂)
1	83.19	110.18	7.51	—	239.77	153.41	11.79	—	5915.10
2	56.39	147.00	16.18	190.10	239.77	153.41	11.79	—	4335.03
3	52.01	144.45	6.59	—	186.93	206.06	15.41	13.95	4713.79
4	44.91	159.98	16.63	160.28	222.14	170.97	12.99	9.68	3974.11

case	Upper-level costs (×10⁴ RMB) Electricity purchase cost	Gas purchase cost	Operation and maintenance cost	Carbon emission cost	Lower-level costs (×10⁴ RMB) Utility function	Energy purchase cost	Carbon emission cost	Carbon emissions (tCO₂)
1	53.58	38.51	16.33	—	1.25	292.48	—	1401.64
2	50.52	39.63	16.11	—	1.22	289.16	0.64	1337.01
3	40.94	49.15	16.07	2.37	1.22	289.16	0.57	1161.78



IV. Obtained Research Achievements

5 papers have been published in SCI Q1 TOP journals including Applied Energy, 4 invention patents have been applied for, and 5 master/doctoral students have been trained.

[1]Wu D, Chang X, Xue Y, et al. Bilevel low-carbon coordinated operation of integrated energy systems considering dynamic tiered carbon pricing methodology. Energy, 2024;310(30):133251.

[2]Wu D, Chang X, Xue Y, et al. Low-carbon energy management strategy for active distribution networks based on dynamic carbon entropy. Journal of Shanghai Jiao Tong University, 2025;59(12):1795-1804. [in Chinese].

[3]Chang X, Lu H, Wu D, et al. Low-Carbon Energy Management Method for Integrated Electricity-Gas-Heat Energy Systems Based on Carbon Entropy Theory and Integrated Energy–Carbon Pricing Mechanism. Energy. (under review).

[1] An integrated energy system energy management method considering low-carbon demand response. Chinese Patent CN202411140174.8, 2024-12-10.

[2An integrated energy system scheduling method and device. Chinese Patent CN202410101944.1, 2024-04-19.

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