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Article

Electricity-Carbon Integration for Zero-Carbon Industrial Parks: A Systematic Framework from Power System Transformation to Carbon Management

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Abstract: Industrial parks are critical hubs of global energy consumption and carbon emissions, contributing approximately one-third of global CO_2 from industrial agglomerations and 31% of China's total emissions. As the ultimate form of low-carbon transition for these clusters, zero-carbon industrial parks have become a central focus for policymakers and researchers worldwide. This paper presents a systematic framework for zero-carbon industrial parks centered on the concept of electricity-carbon integration–the deep coupling of power systems and carbon management systems. The framework encompasses four technical pillars: (1) real-time monitoring of energy and carbon flows using digital twin technology and dynamic emission factors; (2) coordinated optimization through source-grid-load-storage interaction and electricity-carbon joint dispatch, with virtual power plants (VPPs) as a key enabler; (3) deep decarbonization through mature technologies (e.g., BIPV (Building-Integrated Photovoltaics), waste heat recovery) and negative-emission technologies (e.g., CCUS (Carbon Capture, Utilization and Storage), green hydrogen); and (4) closed-loop carbon asset management covering accounting, trading, and compliance. The paper systematically analyzes China's power market reforms, develops VPP (Virtual Power Plant) aggregation and multi-timescale dispatch models, and establishes a comprehensive carbon monitoring system incorporating top-down atmospheric inversion and bottom-up joint monitoring (mass balance + CEMS (Continuous Emission Monitoring Systems)) with a relative deviation reduced from 19.45% to 0.02%. Hourly dynamic carbon emission factors and product carbon footprint accounting methods aligned with international "3-pillar" principles are also developed. Three national-level pilot zero-carbon parks in Datong, Yangjiang, and Yibin demonstrate the feasibility of the proposed framework, achieving renewable energy penetration rates exceeding 95% and carbon emission intensity reductions of over 50% for Scopes 1 and 2 (the core optimization targets of the electricity-carbon dispatch model), while a supplementary Scope 3 accounting module provides full-chain carbon inventory for certification purposes. Based on these findings, the paper proposes the theoretical concept of the Electricity-Carbon Symbiotic Complex (ECSC), which reconceptualizes the relationship between power systems and carbon management from causality to symbiosis, enabling four-dimensional synergies: emission reduction, supply security, cost reduction, and efficiency improvement. Policy recommendations include establishing national technical guidelines for electricity-carbon integration, accelerating the convergence of VPPs with carbon management platforms, and piloting hourly dynamic carbon factors in carbon trading and green power certification.

Keywords: zero-carbon industrial park; electricity-carbon integration; virtual power plant (VPP); dynamic carbon emission factor; carbon management; power market reform

1. Introduction

1.1. Research Background

Global climate governance has entered a new phase, with the IPCC (Intergovernmental Panel on Climate Change) emphasizing the need for substantial, rapid, and sustained emission reductions to achieve net-zero CO_2 targets [1]. As core units of economic development and energy consumption, industrial parks account for approximately 31% of China's national carbon emissions [2] and over 60% of its industrial energy use [3]. Consequently, the transition of industrial parks toward zero-carbon has become a critical pathway for achieving global climate goals [4,5].

1.2. Concept Definition and Evolution of Zero-Carbon Parks

The concept of zero-carbon parks could be traced back to eco-industrial park experiments in Europe and America in the 1970s, which focused on exploring circular economy and industrial symbiosis models to improve resource efficiency and reduce environmental impact through the recycling of by-products, waste, and energy among production facilities within a park and between the park and surrounding urban/rural areas [6]. Since the 1980s, international agreements like the Montreal Protocol and Kyoto Protocol raised global awareness of greenhouse gas emissions, but decarbonization in the industrial sector relied more on voluntary corporate actions before the large-scale commercialization of clean energy technologies [7,8].

It was not until the 2015 Paris Agreement strengthened global emission reduction responsibilities, coupled with the rapid large-scale development of China's photovoltaic and wind power industries driven by national policies, that clean energy costs became commercially viable, making genuine "zero-carbon industrial parks" technologically and economically possible [9]. Currently, academic definitions of zero-carbon parks remain debated. Some scholars argue that the core of a zero-carbon park is achieving net-zero carbon emissions. Li M & Pan J H. define a zero-carbon micro-unit as a micro-economic unit that uses renewable energy for production, storage, and consumption to achieve zero carbon emissions [10]. Building on this, this study defines a zero-carbon park as achieving net-zero emissions within its operational boundary through means such as clean energy substitution, reducing production energy consumption, using Carbon Capture, Utilization and Storage (CCUS), and purchasing green certificates, while also achieving full-scope net-zero emissions (Scope 1, Scope 2, and Scope 3) in corporate operations and supply chains.

The concept of full-scope emissions was first proposed by the Greenhouse Gas (GHG) Protocol in the 1990s and is still used today: Scope 1 refers to direct emissions from production processes; Scope 2 refers to emissions from energy consumption during production; Scope 3 refers to emissions from raw materials, product transportation, and other corporate operational activities [11]. Europe and America, building upon their accumulated experience in certifying enterprises, low-energy buildings, and communities, established a credible set of non-governmental certification systems. Currently, the definition of zero-carbon parks relies mainly on three internationally accepted systems: the GHG Protocol for carbon emission calculation methods [11], ISO (International Organization for Standardization standard for greenhouse gas accounting and verification) 14064 for emission inventories and third-party verification [12], and the Science Based Targets initiative (SBTi) for target setting aligned with the Paris Agreement [13]. In September 2025, the GHG Protocol and ISO announced the development of a unified standard to streamline certification and compliance costs for zero-carbon parks [14].

1.3. Recent Advances in Related Studies

Research on Denmark's Kalundborg industrial symbiosis system started in the 1990s. Scholars have explored emission reduction mechanisms and economic benefits of industrial symbiosis from material flow analysis and ecological network analysis. In recent years, researchers have focused on systematic approaches for applying circular economy principles to zero-carbon park design and evaluating the synergistic contribution of industrial symbiosis to pollution and carbon reduction [15].

European and American scholars have achieved important progress in renewable energy system integration, microgrid optimal dispatch, and virtual power plant aggregation control for parks. Studies include the impacts of high-penetration renewable energy integration on park grid stability and the role of intelligent energy storage in mitigating renewable power fluctuations [16].

Based on international standards including the GHG Protocol, ISO 14064, and SBTi, researchers have developed various carbon accounting methods for parks, discussing life-cycle carbon footprint assessment, carbon offset design, and net-zero pathway planning [11–13]. The joint new standard announced by GHG Protocol and ISO in 2025 will further promote the standardization and mutual recognition of zero-carbon park certification [14].

Chinese academic research on zero-carbon parks emerged after the "dual carbon" goals and has grown rapidly. Tian Jinping and Chen Lüjun's team from Tsinghua University analyzed the significance of constructing zero-carbon coal chemical parks driven by multi-resource coupling of coal, electricity, hydrogen, and new energy, proposing key technical pathways such as precise resource–energy efficiency modeling and industrial chain simulation optimization [17]. Huang XF's team proposed the Complex Network Analysis–Synergy Assessment (CNA–SA) method, integrating inter-firm material flow topology and revealing that industrial chain integrity delivers stronger synergies than diversity, providing a quantitative tool for industrial selection and investment promotion [15].

The power–carbon synergy team at State Grid Shanghai Electric Power Research Institute developed integrated green carbon-reduction technologies for parks, winning the 2025 First Prize of Science and Technology Progress in Energy Conservation and Emission Reduction from the China Energy Conservation Association. Its optimal decision-making method for power–carbon collaborative demand response considering energy-storage carbon footprints supports efficient park decision-making and cost control [18]. The Jiangning Development Zone Energy–Carbon Virtual Power Plant Demonstration Project adopted power–carbon coupling and distribution-microgrid coordination technologies, building a regional multi-level collaborative smart energy–carbon management platform with 200 MW of user-side resources, and was listed in the second batch of National Green and Low-Carbon Advanced Technology Demonstration Projects in April 2025 [19,20].

Liao Maolin et al. reviewed China's park evolution from green governance to zero-carbon development, identifying zero-carbon parks as a core direction of high-quality development [21]. Liu Yueping summarized three types of international zero-carbon parks and their implications for China [22].

1.4. Statement of the Problem

Despite substantial progress in zero-carbon park development worldwide, critical scientific and engineering challenges remain:

- How to quantify the synergistic contribution of industrial symbiosis to pollution and carbon reduction?
- How to realize accurate metering and optimal dispatch of power–carbon synergy?
- How to construct park energy systems adapted to high-penetration renewable energy?
- How to form replicable and scalable zero-carbon park development models?
- How to resolve standard fragmentation and barriers to international mutual recognition?

This study integrated theoretical advances and engineering practices to systematically elaborate China's power–carbon integrated technical system for zero-carbon parks, verify feasibility through national pilot cases, and provide a "Chinese solution" and theoretical reference for industrial park transition under global carbon neutrality [9,17,21]. It should be noted that while the proposed electricity-carbon dispatch model primarily targets Scopes 1 and 2 for real-time operational optimization, a dedicated Scope 3 supply chain accounting module is developed in this study (Section 4.3.2) to complete the full-spectrum carbon inventory. The integration of Scope 3 into the real-time joint dispatch framework is left for future work, as it requires cross-enterprise data sharing mechanisms that are not yet fully established.

2. Methodological Framework of Electricity-Carbon Integration

The core of zero-carbon parks lies in achieving deep integration and synergistic optimization between the energy system and the carbon management system, termed "electricity-carbon integration". This concept originates from a profound understanding of the nature of carbon emissions in industrial parks: approximately 70%–80% of park carbon emissions come from energy activities, among which electricity consumption is the core source. Therefore, the decarbonization of the power system and the precision of carbon management constitute the two pillars of zero-carbon park construction, each being indispensable and mutually reinforcing.

2.1. Connotation and Logic of Electricity-Carbon Integration

The essence of electricity-carbon integration is to break down the barriers between energy flows and carbon data flows, achieving a full-chain closed-loop management of "monitoring – dispatching – accounting – optimization – trading". Its core logic is embodied in three dimensions:

(1) Spatiotemporally Precise Coupling

The power generation structure, power flow distribution, and load profile of the power system directly determine the spatiotemporal distribution of carbon emissions at four levels: hourly, regional, park-level, and enterprise-level. Traditional annual average carbon emission factors cannot reflect real carbon intensity. Dynamic power carbon emission tracing technology enables precise tracking of carbon intensity by hour, by distribution substation area, and by user, providing a data foundation for time-segmented and area-specific emission reduction in parks.

(2) Multi-Objective Collaborative Optimization

The power system pursues a balance among four objectives: security, economy, cleanliness, and reliability. The carbon management system pursues two objectives: minimizing emissions and minimizing costs. Electricity-carbon integration, through a unified optimization objective function, transforms carbon constraints into economic signals for power system operation, achieving synergy among four goals: carbon reduction, supply security, cost reduction, and efficiency enhancement, without sacrificing power supply stability or enterprise benefits solely for emission reduction.

(3) Three-Tier Market Linkage

Green power trading, carbon trading, and the electricity spot/ancillary services market have inherent value linkages. Electricity-carbon integration connects price signals, certification mechanisms, data interoperability, and settlement closure, enabling the value conversion of green power consumption, carbon emission reduction, and power demand response, thereby transforming park emission reduction outcomes from a “cost item” into a “revenue item”.

2.2. Key Technological Enablers for Electricity-Carbon Integration

The realization of electricity-carbon integration required the synergistic support of four major technology systems:

(1) Precise Perception: Integrated Real-Time Monitoring Platform for Energy and Carbon Flows

Core upgrade: Upgrading from “coverage monitoring” to full-dimensional, verifiable, second-level synchronized integrated perception, addressing the pain points of traditional carbon accounting such as “incomplete coverage, inaccurate data, manual reporting, and untraceability”.

Monitoring scope: Covered three levels: park grid side, enterprise side, and equipment side, including enterprise electricity/gas/heat consumption, distributed PV (Photovoltaic)/wind power/storage, charging piles, and full energy consumption ports of industrial production lines.

Technological enablers:

1. Digital twin: Constructed a 1:1 digital mapping of energy and carbon flows, enabling visualization and traceability of carbon flow trajectories.
2. Dynamic factor calculation: Adopted hourly regional power carbon footprint factors to replace fixed default values.
3. Joint monitoring: Coupled automatic flue gas monitoring with automatic material balance accounting for dual-data cross-checking.
4. IoT access: Achieved second-level data acquisition through edge computing gateways and smart energy monitoring terminals.

Implementation outcomes: Precise traceability of carbon footprint; 10%–15% improvement in comprehensive energy efficiency; data accuracy exceeding 99%.

(2) Collaborative Optimization: Source-Grid-Load-Storage Interaction and Electricity-Carbon Joint Dispatch

Core upgrade: Upgrading from "optimal dispatch" to coordinated operation encompassing four-level regulation, multi-scenario response, and market-based trading, achieving carbon synergy across the entire source-grid-load-storage chain.

Regulation system: Established a four-level low-carbon control system comprising distribution network master station, distribution substation area terminals, energy regulation platform, and charging piles.

Core scenarios:

1. Electricity-carbon collaborative regulation of park-level PV-storage-charging integration with V2G (Vehicle-to-Grid).
2. Virtual power plants aggregating distributed resources to participate in demand response, power ancillary services, and spot markets.
3. Cross-regional complementary dispatch of energy-carbon resources to smooth renewable energy fluctuations.

Technological enablers: Generation/load/price forecasting, adjustable potential analysis, resource aggregation, optimal dispatch, coordinated control, and trading decision support.

Implementation outcomes: Renewable energy utilization rate increased to over 95%; adjustable load response speed reaching the minute level.

(3) Deep Decarbonization: Technology Integration and Large-Scale Application of Negative-Emission Technologies

Core upgrade: Upgrading from "technology application" to a deep decarbonization system encompassing full coverage of mature technologies, piloting of frontier technologies, and circular utilization, balancing emission reduction intensity with sustainability.

Mature decarbonization technologies:

1. Building-integrated photovoltaics (BIPV), rooftop distributed PV, and on-site direct green power supply.
2. Electricity substitution for gas/oil, and recovery and utilization of industrial waste heat, waste cooling, and waste pressure.
3. Green power substitution combined with green certificate offsetting to achieve zero indirect emissions from electricity consumption.

Frontier negative-emission technologies:

1. Direct air capture (DAC) and industrial flue gas carbon capture, utilization, and storage (CCUS).
2. Green hydrogen synthesis of chemicals (CO/CO_2 + green hydrogen), and hydrogen substitution in coal chemical and steel industries.

Circular pathway: Constructed a synergistic model of "negative-emission technologies + ecological circulation + low-carbon industry" to achieve deep decarbonization.

(4) Management Closed-Loop: Full-Process Operation of Carbon Accounting–Carbon Trading–Carbon Assets

Core upgrade: Upgrading from "carbon management" to full life-cycle carbon asset operation encompassing compliance fulfillment, value realization, and financial innovation.

Management process: Covered the entire process of carbon monitoring – carbon accounting – carbon verification – carbon trading – carbon compliance – carbon asset management.

Market participation: Interfaced with the national carbon market, the voluntary emission reduction market (CCER (China Certified Emission Reduction)), and the green power/green certificate market.

Value-added services: Provided enterprises with carbon footprint accounting, CBAM (Carbon Border Adjustment Mechanism) response, green supply chain management, and carbon financial services.

Digital enablers: An electricity-carbon integration platform incorporating AI algorithms to achieve automated carbon asset valuation and trading strategy optimization.

2.3. Value Creation of Electricity-Carbon Integration

The implementation of electricity-carbon integration creates multi-dimensional value for zero-carbon parks:

(1) Economic Benefits

- Green power direct supply reduces energy costs by 15%–30%.
- Demand response and ancillary services generate market-based revenue, with annual revenue for a single park reaching the million-yuan level.
- Carbon asset trading enables monetization, directly converting emission reductions into economic returns.

(2) Security Benefits

- Virtual power plants aggregate distributed resources, enhancing the supply–demand balance capacity of the power grid.
- Source-grid-load-storage coordination improves power supply reliability by over 20% under extreme weather conditions.
- Incremental distribution networks provide a backup, avoiding power supply interruptions caused by renewable energy fluctuations.

(3) Environmental Benefits

- High-penetration renewable energy consumption reduces Scope 1 and Scope 2 carbon emission intensity in parks by over 50%.
- Carbon emissions per unit of energy consumption met the standard ($\leq$ 0.2 t CO_2/tce (ton of standard coal equivalent)), satisfying national zero-carbon park requirements.

(4) Social Benefits

- Assists enterprises in responding to the EU (European Union) CBAM and green trade barriers, enhancing the international competitiveness of products.
- Establishes zero-carbon benchmarks, attracting green investment and optimizing the park's business environment.

2.4. Research Methodology

This study follows a four-stage research methodology to ensure the rigor, reproducibility, and practical relevance of the proposed framework:

(1) Literature review and gap analysis: We conducted a systematic review of existing studies on integrated energy systems, virtual power plants (VPPs), carbon management, and zero-carbon park development (Sections 1.3 and 1.4). This stage identified the research gaps that motivate our work, particularly the lack of a unified framework that couples real-time power system operation with dynamic carbon accounting.

(2) Conceptual framework design: Based on the gap analysis, we designed the Electricity-Carbon Symbiotic Complex (ECSC) concept and the overall electricity-carbon integration framework (Sections 2.1–2.3). The framework development followed a top-down approach, starting from system-level architecture and progressively refining to component-level functions.

(3) Mathematical modeling and simulation: We developed quantitative models for each key module, including VPP aggregation and dispatch (Sections 3.3–3.4), dynamic carbon emission factor calculation (Section 4.2), product carbon footprint accounting (Section 4.3), and carbon asset management (Section 4.4). Model parameters were calibrated using data from the pilot parks.

(4) Engineering validation through case studies: The proposed framework was validated through three national-level zero-carbon pilot parks (Datong, Yangjiang, Yibin). These parks were selected based on three criteria: (a) representativeness of different industrial types (resource-based, manufacturing, and high-tech); (b) completeness of monitoring data infrastructure; and (c) official designation as national pilots. Model validation followed a three-step procedure: theoretical derivation consistency checking, numerical simulation under controlled conditions, and field pilot verification with actual park operation data (Section 5.3).

3. Power System Foundation for Zero-Carbon Parks

The energy foundation of zero-carbon parks was the new power system. Compared with traditional power systems, the new power system is characterized by a high proportion of renewable energy integration, deep interaction between source, grid, load, and storage, and the gradual improvement of electricity market mechanisms. This chapter systematically elaborated on the key technologies of new power systems supporting the construction of zero-carbon parks, including the institutional background of electricity market reform, the core technologies and architecture of virtual power plants (VPPs), and multi-timescale optimal dispatch models.

3.1. Institutional Background of China's Electricity Market Reform

3.1.1. The Process of China's Electricity Market Reform

China's electricity market reform went through three important stages, providing an institutional foundation for zero-carbon parks to participate in the electricity market.

Stage 1 (1998–2015): Separation of generation and grid, and market exploration. In 1998, the Ministry of Electric Power was abolished and the State Power Corporation was established. In 2002, Document No. 5 initiated the first electricity reform, achieving "separation of generation and grid" and introducing competition on the generation side, forming a pattern where five major power generation groups coexisted with various types of generation capital.

Stage 2 (2015–2022): Opening of the power sales side. In 2015, Document No. 9 launched the second electricity reform. The first phase opened the power sales side, allowing social capital to enter incremental distribution networks and power sales, forming a wholesale/retail competition pattern.

Stage 3 (2022–present): Development of a national unified electricity market system. In 2022, Document No. 118 initiated the construction of a national unified electricity market system, requiring initial completion by 2025 and basic completion by 2030. In 2026, Document No. 4 further improved the market system, promoting the full participation of diverse power generation entities. By 2030, market-based electricity transactions were expected to account for about 70% of total social electricity consumption.

3.1.2. Recent Key Policies

Since 2025, a series of major policies have been intensively issued, providing policy guarantees for the development of new business forms such as VPPs and direct green power connections:

- February 2025–Document No. 136: Promoted the full entry of renewable energy into the electricity market and encouraged VPPs to aggregate distributed PV, wind power, energy storage, and adjustable loads.
- April 2025–Document No. 357: Required VPP regulation capacity to reach 20 GW by 2027 and 50 GW by 2030.
- May 2025–Document No. 650: Defined the implementation path for direct green power connections, requiring that wind and PV power be supplied directly to single power users without connecting to the public grid.
- February 2026–Document No. 4: Proposed "one-place registration, nationwide sharing" to enable cross-operational zone trading, supporting flexible participation of new business entities such as microgrids and adjustable loads.

3.2. Multidimensional Value of Electricity Markets and Characteristics of New Power Systems

3.2.1. Multidimensional Value of Electricity as a Commodity

In new power systems, the value of electricity expands from a single energy value to a multidimensional value system:

$$V_{\text{total}} = V_{\text{energy}} + V_{\text{capacity}} + V_{\text{flexibility}} + V_{\text{clean}} \tag{1}$$

where:

V_{total}: Total value of electricity.

V_{energy}: Energy value, realized through spot markets.

V_{capacity}: Capacity value, realized through capacity markets.

$V_{\text{flexibility}}$: Flexibility value, realized through ancillary service markets.

V_{clean}: Clean value, realized through green power trading markets.

3.2.2. New Characteristics of New Power Systems

(1) Deep interaction between source, grid, load, and storage

Traditional systems follow a "load-following generation" model. In new systems, the variability of renewables increases the need for regulation resources, requiring source – grid – load – storage interaction to maintain balance.

(2) Distributed entities as core components

By 2030, about 49.3% of new PV capacity (approx. 500 GW) is expected to come from distributed sources. These will trade directly within distribution networks, enabling local supply–demand balance.

3.3. Virtual Power Plant: Technical Architecture and Core Models

A Virtual Power Plant (VPP) is a coordination and management system that aggregates distributed resources such as generation, storage, and adjustable loads, enabling them to participate in electricity markets and grid operations as a single entity.

3.3.1. Operation Modes of VPPs

A VPP can act as a "positive power plant" by supplying power to the grid or as a "negative power plant" by increasing load consumption. Its core lies in forming a controllable flexibility resource pool. The external transaction mode of the virtual power plant is shown in **Figure 1**.

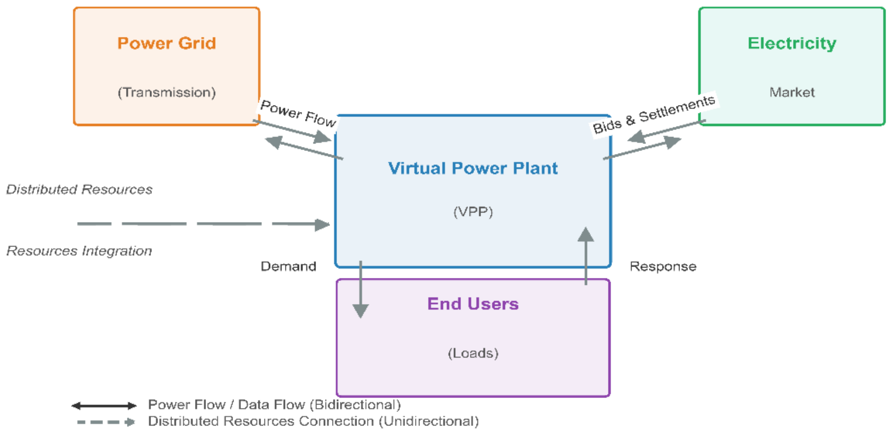

Figure 1. External trading mode of a virtual power plant. Arrows indicate the bidirectional flow of electricity and information between the VPP and the power grid, electricity market, and end-users.

3.3.2. Technical Architecture of VPPs

The VPP architecture consists of four layers: perception layer, network layer, platform layer, and application layer. **Figure 2** presents the full technical architecture of a virtual power plant.

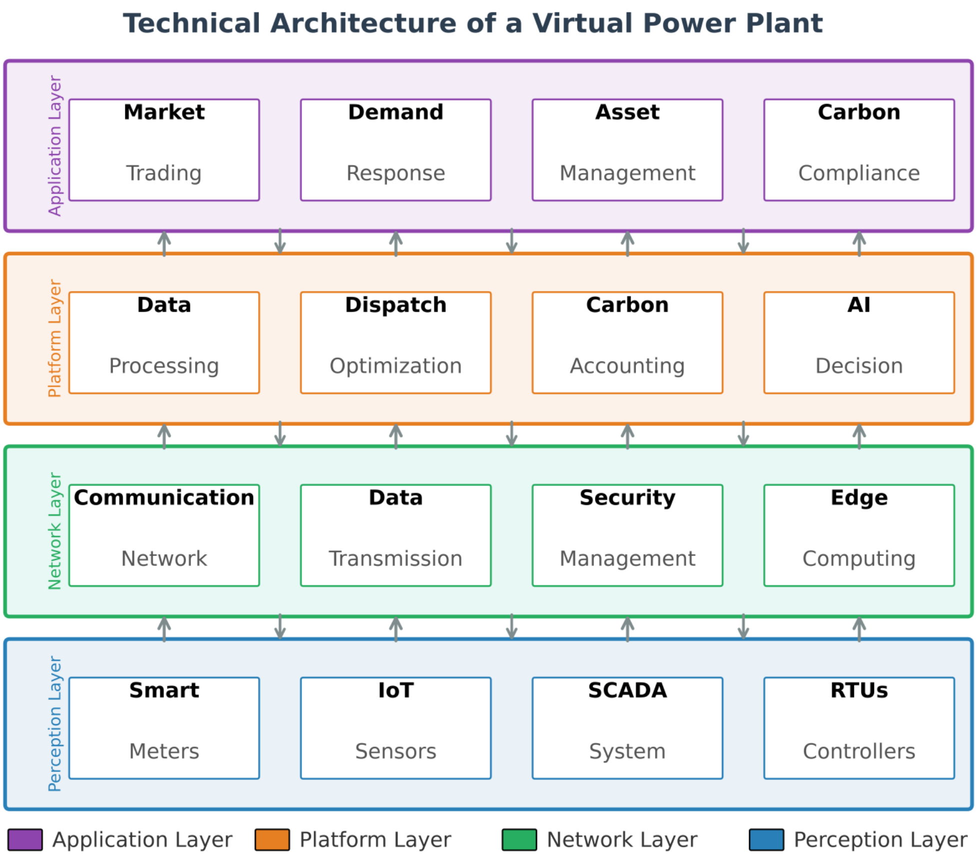

Figure 2. Technical architecture of a virtual power plant (perception layer, network layer, platform layer, application layer). Arrows represent the upward data flow from perception to application and the downward control flow from application to perception, forming a closed-loop management system.

3.3.3. Aggregation and Optimization Models of VPPs

(1) Aggregated power range

$$P_{\mathrm{VPP}}^{\min} = \sum_{\mathrm{i}=1}^{N} P_{\mathrm{i}}^{\min} \tag{2}$$

$$P_{\mathrm{VPP}}^{\max} = \sum_{\mathrm{i}=1}^{N} P_{\mathrm{i}}^{\max} \tag{3}$$

where,

$P_{\mathrm{VPP}}^{\min}$: Minimum aggregated output of the virtual power plant (MW), i.e., the sum of the minimum outputs of all distributed energy resources.

$P_{\mathrm{VPP}}^{\max}$: Maximum aggregated output of the virtual power plant (MW), i.e., the sum of the maximum outputs of all distributed energy resources.

$P_{\mathrm{i}}^{\min}$: Minimum output of the i-th distributed energy resource (MW); for adjustable loads, this value can be negative.

$P_{\mathrm{i}}^{\max}$: Maximum output of the i-th distributed energy resource (MW).

N: Total number of distributed energy resources aggregated by the virtual power plant. (Adapted from [16])

(2) Aggregated ramping capability

$$R_{\mathrm{VPP}}^{\mathrm{down}} = \min\left(\sum_{i=1}^{N} R_{\mathrm{i}}^{\mathrm{down}}, \frac{\Delta P_{\mathrm{vpp}}}{\Delta t}\right) \tag{4}$$

$$R_{\mathrm{VPP}}^{\mathrm{UP}} = \min\left(\sum_{i=1}^{N} R_{\mathrm{i}}^{\mathrm{UP}}, \frac{\Delta P_{\mathrm{vpp}}}{\Delta t}\right) \tag{5}$$

where,

$R_{\mathrm{VPP}}^{\mathrm{up}}$: Upward ramp rate of the virtual power plant (MW/min), i.e., the amount of output that can be increased per unit time.

$R_{\mathrm{VPP}}^{\mathrm{down}}$: Downward ramp rate of the virtual power plant (MW/min), i.e., the amount of output that can be decreased per unit time.

$R_{\mathrm{i}}^{\mathrm{up}}$: Upward ramp rate of the i-th resource (MW/min).

$R_{\mathrm{i}}^{\mathrm{down}}$: Downward ramp rate of the i-th resource (MW/min).

ΔP_{VPP}: Change in output of the virtual power plant (MW).

Δ_t: Change in time (min).

(Adapted from [16])

(3) Revenue model for VPP participation in electricity markets

$$\max \sum_{t=1}^{T} \left[\lambda_{\mathrm{t}}^{\mathrm{market}} \cdot P_{\mathrm{VPP,t}} - \sum_{i=1}^{N} c_{\mathrm{i}}\left(P_{\mathrm{i,t}}\right)\right] \tag{6}$$

Constraints:

Resource output constraints:

$$P_{\mathrm{i}}^{\mathrm{min}} \leq P_{\mathrm{i,t}} \leq P_{\mathrm{i}}^{\mathrm{max}} \tag{7}$$

Resource ramp rate constraints:

$$\left| P_{\mathrm{i,t}} - P_{\mathrm{i,t-1}} \right| \leq R_{\mathrm{i}} \cdot \Delta t \tag{8}$$

Energy storage energy constraints:

$$SOC_{\mathrm{min}} \leq SOC_{\mathrm{t}} \leq SOC_{\mathrm{max}} \tag{9}$$

Virtual power plant power balance:

$$\sum_{i=1}^{N} P_{i,t} = P_{\mathrm{VPP,t}} \tag{10}$$

where,

t: Time index, $t = 1, 2, \ldots, \mathrm{T}$, where T is the total number of time periods in the dispatch cycle.

$\lambda_{\mathrm{t}}^{\mathrm{market}}$: Market electricity price at time t (yuan/MWh), determined by the electricity market clearing.

$P_{\mathrm{VPP},t}$: Net output of the virtual power plant at time t (MW). A positive value indicates power supply to the grid, and a negative value indicates power consumption from the grid.

$P_{\mathrm{i,t}}$: Output of the i-th resource at time t (MW).

$c_{\mathrm{i}}(P_{\mathrm{i,t}})$: Cost function of the i-th resource when operating at output $P_{\mathrm{i,t}}$ (yuan/h), typically in quadratic form.

R_i: Ramp rate limit of the i-th resource (MW/min).

SOC_t: State of charge of the energy storage system at time t (%).

SOC_{min}、SOC_{max}: Minimum and maximum state of charge of the energy storage system.

(Adapted from [16])

3.4. Source – Grid – Load – Storage Collaborative Optimization Model

3.4.1. Multi-Timescale Scheduling Framework

The new power system in zero-carbon parks requires coordinated optimization across multiple timescales, including day-ahead scheduling, intraday rolling optimization, and real-time control. **Figure 3** presents the multi-timescale scheduling framework for virtual power plants.

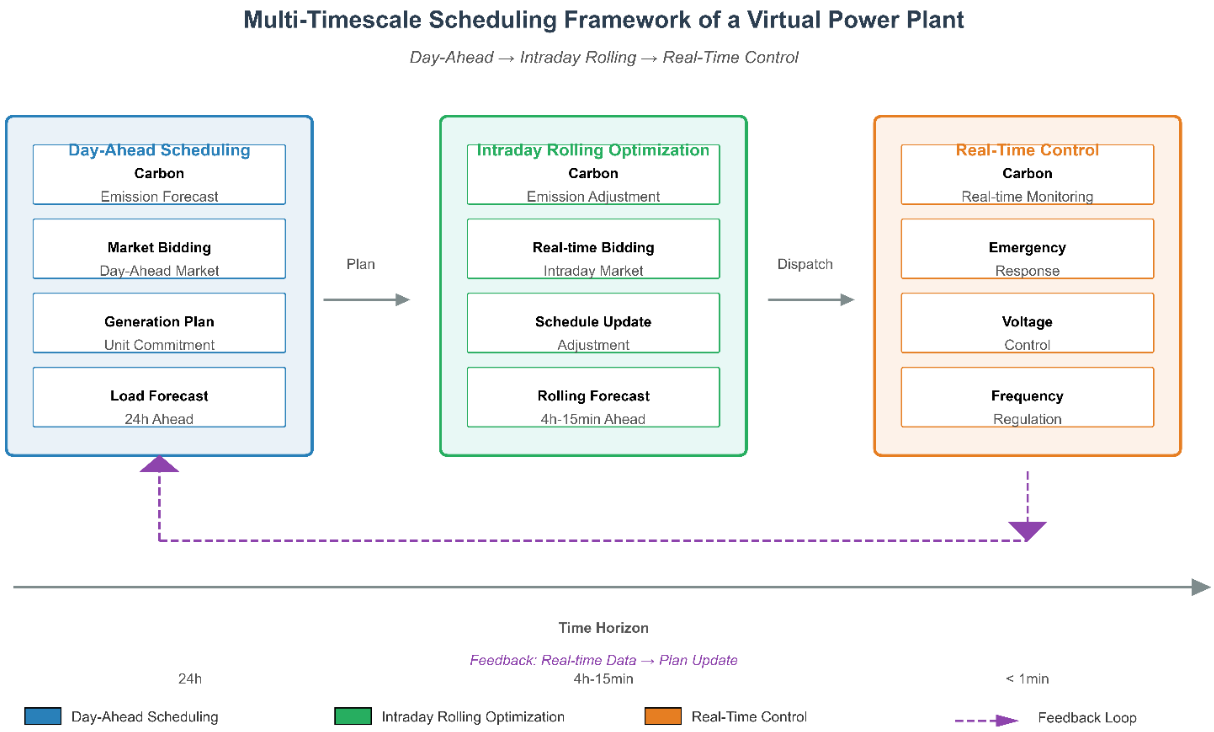

Figure 3. Multi-timescale scheduling framework of a virtual power plant (day-ahead, intraday rolling, real-time control). Arrows illustrate the temporal progression and feedback adjustment across different timescales, enabling coordinated dispatch from long-term planning to real-time execution.

3.4.2. Day-Ahead Optimal Dispatch Model

(1) Objective function

The day-ahead optimization aims to minimize the operating cost as follows:

$$\min \sum_{t=1}^{24}\left(C_{\mathrm{grid}}\left(P_{\mathrm{grid,t}}\right)+\sum_{i=1}^{N} C_{\mathrm{i}}\ \left(P_{\mathrm{i,t}}\right)+C_{\mathrm{DR}}\left(P_{\mathrm{DR,t}}\right)\right) \tag{11}$$

where,

t: Time index, $t = 1, 2, \ldots, 24$, representing the 24 hours of a day.

$C_{grid}(P_{grid})$: Cost function of purchasing electricity from the grid at time t (yuan/h), where P_{grid} is the purchased power.

$C_i(P_{i,t})$: Operating cost function of the i-th distributed resource when operating at output $P_{i,t}$ (yuan/h).

$C_{DR}(P_{DR,t})$: Demand response cost function (yuan/h), where $P_{DR,t}$ is the load reduction power from demand response.

N: Total number of distributed resources.

(Adapted from [16])

(2) Power balance constraint

$$P_{\mathrm{grid,t}} + \sum_{i=1}^{N_{\mathrm{gen}}} P_{\mathrm{gen,i,t}} + P_{\mathrm{dis,t}} = P_{\mathrm{load,t}} + \sum_{i=1}^{N_{\mathrm{DR}}} P_{\mathrm{DR,i,t}} + P_{\mathrm{ch,t}} \tag{12}$$

where,

$P_{grid,t}$: Power purchased from the grid by the park/industrial park at time t (MW).

N_{gen}: Total number of distributed generation resources.

P_{gen}: Output of the i-th distributed generation resource (e.g., solar PV, wind power) at time t (MW).

$P_{dis,t}$: Discharge power of the energy storage system at time t (MW).

$P_{load,t}$: Total load power of the park/industrial park at time t (MW).

N_{DR}: Total number of demand response resources.

$P_{DR,i,t}$: Load power reduced by the i-th demand response resource at time t (MW).

$P_{ch,t}$: Charge power of the energy storage system at time t (MW).

(Adapted from [16])

(3) Storage system constraints

The dynamic model of the energy storage system is:

$$SOC_{\mathrm{t}} = SOC_{\mathrm{t-1}} + \eta_{\mathrm{ch}} P_{\mathrm{ch,t}} \Delta t - \frac{P_{\mathrm{dis},t}}{\eta_{\mathrm{dis,t}}} \Delta t \tag{13}$$

Constraints:

$$SOC_{\min} \leq SOC_{\mathrm{t}} \leq SOC_{\max} \tag{14}$$

$$0 \leq P_{\mathrm{ch,t}} \leq P_{\mathrm{ch}}^{\max} \cdot U_{\mathrm{ch,t}} \tag{15}$$

$$0 \leq P_{\mathrm{dis,t}} \leq P_{\mathrm{dis}}^{\max} \cdot U_{\mathrm{dis,t}} \tag{16}$$

$$u_{\mathrm{ch,t}} + u_{\mathrm{dis,t}} \leq 1 \tag{17}$$

where,

SOC_t: State of charge of the energy storage system at time t (%), representing the ratio of remaining energy to rated capacity.

η_{ch}: Charging efficiency of the energy storage system (%), indicating the energy conversion efficiency during the charging process.

η_{dis}: Discharging efficiency of the energy storage system (%), indicating the energy conversion efficiency during the discharging process.

Δt: Time step (h), typically taken as 1 hour.

SOC_{min}、SOC_{max}: Minimum and maximum state of charge of the energy storage system (%), typically set to 10% and 90%.

P_{ch}^{max}、P_{dis}^{max}: Maximum charging power and maximum discharging power of the energy storage system (MW).
$u_{ch,t}$、$u_{dis,t}$: Charging and discharging state variables at time t, taking values of 0 or 1, indicating whether the system is in the charging/discharging state.
(Adapted from [16])

3.4.3. Market Clearing Model with VPP Participation

In the electricity spot market, market clearing follows the principle of minimizing social cost:

$$\min \sum_{t=1}^{T} \left(\sum_{g=1}^{G} C_g \left(P_{g,t}\right) + \sum_{v=1}^{V} C_v \left(P_{v,t}\right) \right) \tag{18}$$

Constraints:
System power balance:

$$\sum_{g=1}^{G} P_{g,t} + \sum_{v=1}^{V} P_{v,t} = D_t \tag{19}$$

Transmission capacity constraints:

$$\left| P_{line,I,t} \right| \le P_{line,I}^{max} \tag{20}$$

Storage system constraints (SOC dynamics, SOC bounds, charge/discharge power limits, and charge/discharge exclusivity) follow the same formulations as defined in Section 3.4.2.

Generator output constraints and VPP output constraints follow the same lower/upper bound formulations as defined in Section 3.3.3.

where,
t: Time index, $t = 1, 2, \ldots, T$, where T is the total number of time periods in the dispatch cycle.
g: Generator index, $g = 1, 2, \ldots, G$, where G is the total number of generators.
v: Virtual power plant index, $v = 1, 2, \ldots, V$, where V is the total number of virtual power plants.
$C_g(P_{g,t})$: Bid function of generator g when operating at output $P_{g,t}$ (yuan/MWh).
$C_v(P_{v,t})$: Bid function of virtual power plant v when operating at output $P_{v,t}$ (yuan/MWh).
$P_{g,t}$: Output of generator g at time t (MW).
$P_{v,t}$: Output of virtual power plant v at time t (MW).
D_t: Total system load at time t (MW).
$P_{line,l,t}$: Active power flow on transmission line l at time t (MW), l = 1, 2, …, L.
$P_{line,l}^{max}$: Maximum transmission capacity of transmission line l (MW).
P_g^{min}、P_g^{max}: Minimum and maximum output of generator g (MW).
P_v^{min}、P_v^{max}: Minimum and maximum output of virtual power plant v (MW).
(Adapted from [16])

3.5. Economic Benefits and Application Case of VPP

(1) Investment savings

By constructing a virtual power plant to replace traditional coal-fired units to meet peak load demand, significant investment savings can be achieved.

$$\Delta I = l_{\text{coal}} - l_{\text{vpp}} \tag{21}$$

where,

ΔI: Investment savings (100 million yuan).

l_{coal}: Investment required for constructing coal-fired units to meet peak load (100 million yuan).

l_{VPP}: Investment required for constructing a virtual power plant (100 million yuan).

(Adapted from industry data and [16])

According to estimates, meeting a 5% peak load demand by constructing coal-fired units requires an investment of approximately 400 billion yuan, while constructing a virtual power plant requires only 40–57 billion yuan, resulting in investment savings of over 85%.

(2) User revenue

After participating in a virtual power plant, users can obtain demand response benefits:

$$R_{\text{user}} = \sum_{t=1}^{T} \left(\lambda_{\text{DR,t}} \cdot P_{\text{DR,t}} + \lambda_{\text{market,t}} \cdot \left(P_{\text{base,t}} - P_{\text{actual,t}}\right)\right) \tag{22}$$

where,

R_{user}: Total revenue of the user (yuan).

$\lambda_{\text{DR,t}}$: Demand response compensation price at time t (yuan/MWh).

$P_{\text{DR,t}}$: Load power reduced by the user at time t (MW).

$\lambda_{\text{market,t}}$: Market electricity price at time t (yuan/MWh).

$P_{\text{base,t}}$: Baseline load of the user at time t (MW), i.e., the load when not participating in the virtual power plant.

$P_{\text{actual,t}}$: Actual load of the user at time t after participating in the virtual power plant (MW).

(Adapted from [16])

(3) System benefit

The regulation value provided by a virtual power plant to the power system can be quantified as:

$$V_{\text{flex}} = \sum_{t=1}^{T} \lambda_{\text{flex,t}} \cdot \left(P_{\text{vpp,t}}^{\text{up}} + P_{\text{vpp,t}}^{\text{down}}\right) \tag{23}$$

where,

V_{flex}: Total value of flexible regulation provided by the virtual power plant (yuan).

$\lambda_{\text{flex,t}}$: Marginal value of flexible regulation resources for the system at time t (yuan/MW).

$P_{\text{VPP,t}}^{\text{up}}$: Upward regulation capacity of the virtual power plant at time t (MW).

$P_{\text{VPP,t}}^{\text{down}}$: Downward regulation capacity of the virtual power plant at time t (MW).

(Adapted from [16])

(4) VPP Application Case: Wuhu City-Level VPP

Virtual power plants have been implemented in practice across many cities in China. **Figure 4** presents the overall architecture of the city-level virtual power plant in Wuhu.

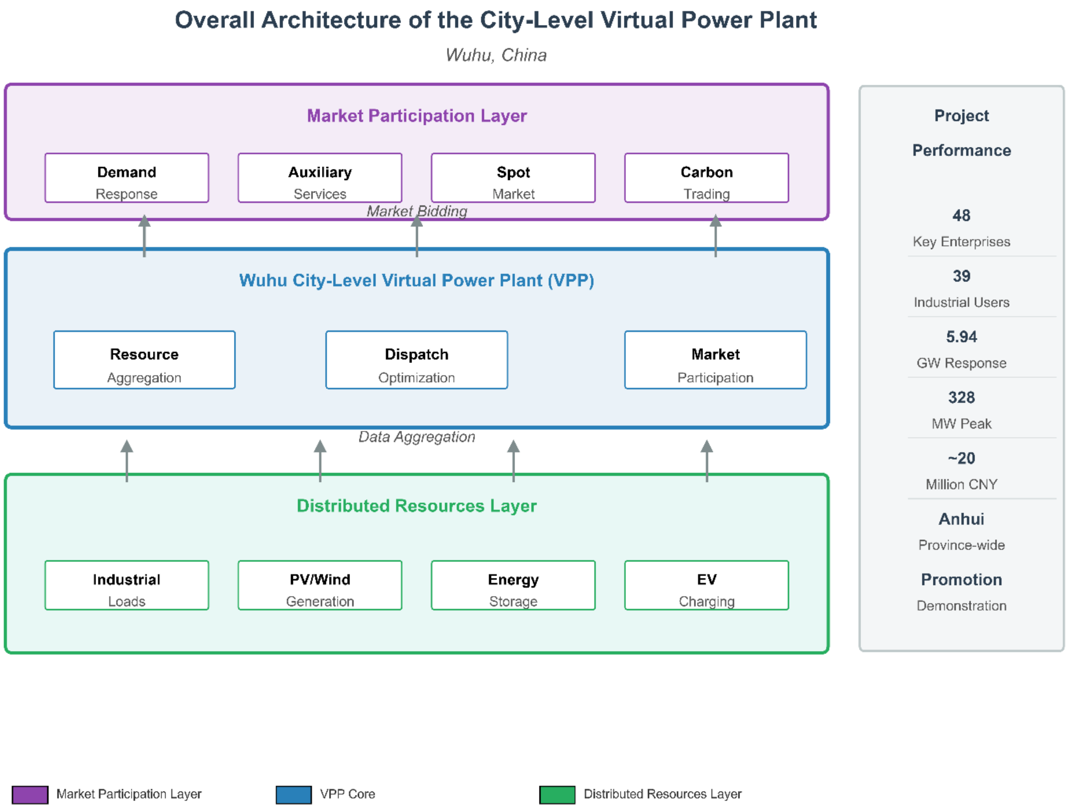

Figure 4. Overall architecture of the city-level virtual power plant in Wuhu, China. Arrows depict the integration of distributed resources (generation, storage, and loads) through the VPP platform, enabling unified participation in grid dispatch and electricity markets.

The Wuhu VPP project achieved the following during its first phase:

- Energy data access and display for 48 key enterprises
- Flexible load control access for 39 major industrial users, covering 60% of the city's industrial electricity consumption
- During summer 2022 peak demand: participated in 25 provincial demand response events, accumulated response load of 5.94 GW, with a single-day peak of 328 MW, earning users ~20 million CNY in subsidies

The success of this project has led to its promotion across Anhui Province.

3.6. Brief Summary

This chapter systematically elaborated on key technologies of new power systems supporting zero-carbon parks. It reviewed the institutional background of China's electricity market reform, analyzed the multidimensional value of electricity and new characteristics of power systems, and focused on VPP technical architecture, aggregation models, and optimization algorithms, including multi-timescale scheduling, day-ahead optimization, and market clearing models. Finally, the Wuhu VPP case validated the benefits of VPP technology in enhancing grid regulation and reducing user energy costs. This chapter provides the power system theoretical foundation for subsequent integration of power and carbon technologies.

4. Carbon Emission Management Technology System

The carbon emission management technology system for zero-carbon parks serves as a key enabler for precise emission reduction, carbon trading compliance, and response to international trade barriers. This chapter systematically elaborates on carbon emission monitoring technologies, electricity carbon tracing technologies, product carbon footprint accounting methods, and management-based carbon reduction mechanisms, establishing a full-chain carbon emission management technology system covering "monitoring – accounting – tracing – management".

4.1. Carbon Emission Monitoring Technology System

4.1.1. Top-Down Regional Carbon Monitoring Technology

Based on the national greenhouse gas monitoring network established by the CMA Greenhouse Gases and Carbon Neutrality Monitoring and Assessment Center, coupled monitoring technology integrating observation networks and carbon satellites is applied to build a supporting technology system for carbon source and sink monitoring and verification. This forms a "top-down" regional carbon emission inversion system, enabling near-real-time monitoring of anthropogenic carbon emissions at the province – city – district three-level integration with a spatial resolution of 1 km × 1 km.

The basic principle of regional carbon emission inversion uses atmospheric greenhouse gas concentration observations combined with atmospheric transport models to infer regional carbon emission fluxes:

$$\frac{\partial C}{\partial t} = \nabla \cdot (K \nabla C) - \nabla \cdot (uC) + S(\mathrm{x,y,t}) - R(\mathrm{x,y,t}) \tag{24}$$

where:

C: Atmospheric CO_2 concentration (ppm).

t: Time (s).

K: Turbulent diffusion coefficient (m^2/s).

u: Wind velocity vector (m/s).

S(x,y,t): Carbon emission source term (kg/($m^2 \cdot s$)), i.e., the regional carbon flux to be inverted.

R(x,y,t): Carbon sink uptake term (kg/($m^2 \cdot s$)).

(Adapted from atmospheric inversion modeling literature)

By solving the above inverse problem, a regional carbon emission distribution with a spatial resolution of 1 km × 1 km and hourly temporal resolution can be obtained.

4.1.2. Bottom-Up Joint Monitoring Technology

Carbon emission monitoring and accounting methods fall into two categories: the mass balance method and the flue gas monitoring method (CEMS). The joint monitoring method is currently the most reliable and practical solution.

(1) Mass Balance Method

The mass balance method calculates carbon emissions based on activity data and emission factors:

$$E_{\text{mass}} = \sum_{j=1}^{M} \left(AD_{\text{j}} \times EF_{\text{j}}\right) \tag{25}$$

where:

E_{mass}: Total carbon emissions calculated by the mass balance method (t CO_2).

AD_{j}: Activity data of the j-th fuel or raw material (t, m^3, or kWh).

EF_{j}: Emission factor of the j-th fuel or raw material (t CO_2/unit).

M: Number of fuel or raw material types.

(Original)

(2) Flue Gas Monitoring Method (CEMS)

The CEMS method calculates carbon emissions based on real-time monitoring of flue gas concentration and flow rate:

$$E_{\text{CEMS}} = \sum_{t=1}^{T} \left(Q_{\text{t}} \times \rho_{\text{CO}_2\text{,t}} \times \Delta t\right) \tag{26}$$

where:

E_{CEMS}: Total carbon emissions calculated by the CEMS method (t CO_2).

Q_{t}: Flue gas flow rate at time t (m^3/h).

$\rho_{\text{CO2,t}}$: CO_2 concentration in flue gas at time t (t CO_2/m^3).

Δt: Time step (h).

T: Total number of time periods in the monitoring period.

(Original)

(3) Joint Monitoring Method

The joint monitoring method establishes a correlation model between mass balance data and CEMS data, enabling cross-validation and improved data quality:

$$\widehat{E} = \alpha E_{\text{mass}} + (1\text{-}\alpha)\, E_{\text{CEMS}} + \beta \cdot f(X) \tag{27}$$

where:

$\widehat{E}$: Estimated total carbon emissions using the joint monitoring method (t CO_2).

α: Weight coefficient of the mass balance method, $0 \leq \alpha \leq 1$.

E_{mass}: Result of the mass balance method (t CO_2).

E_{CEMS}: Result of the CEMS method (t CO_2).

β: Correction coefficient.

$f(X)$: Correction function based on operating parameters X.

(Original)

The correction function $f(X)$ adjusts for deviations between the two methods based on operating conditions:

$$f(X) = \gamma_0 + \textstyle\sum_{\text{k}=1}^{K} \gamma_{\text{k}} \cdot X_{\text{k}} \tag{28}$$

where:

γ_0: Constant term.

γ_{k}: Regression coefficient of the k-th operating parameter.

X_k: k-th operating parameter (e.g., load factor, fuel quality).

K: Number of operating parameters.

(Original)

Data quality assessment indicators for the joint monitoring method include:

Relative deviation:

$$RD = \frac{|E_{\mathrm{mass}} - E_{\mathrm{CEMS}}|}{E_{\mathrm{true}}} \times 100\% \quad (29)$$

Fraud detection rate:

$$P_{\mathrm{detect}} = \frac{N_{\mathrm{detect}}}{N_{\mathrm{fraud}}} \times 100\% \quad (30)$$

where:

RD: Relative deviation (%).

E_{true}: True carbon emissions (t CO_2).

P_{detect}: Fraud detection rate (%).

N_{detect}: Number of successfully detected fraudulent samples.

N_{fraud}: Total number of fraudulent samples.

(Original)

Figure 5 presents the overall architecture of the carbon emission monitoring technology system, including top-down regional monitoring, bottom-up enterprise monitoring, and the core principles of the joint monitoring method. This figure corresponds to Section 4.1. Additional uncertainty and sensitivity analyses are presented in Section 4.5.

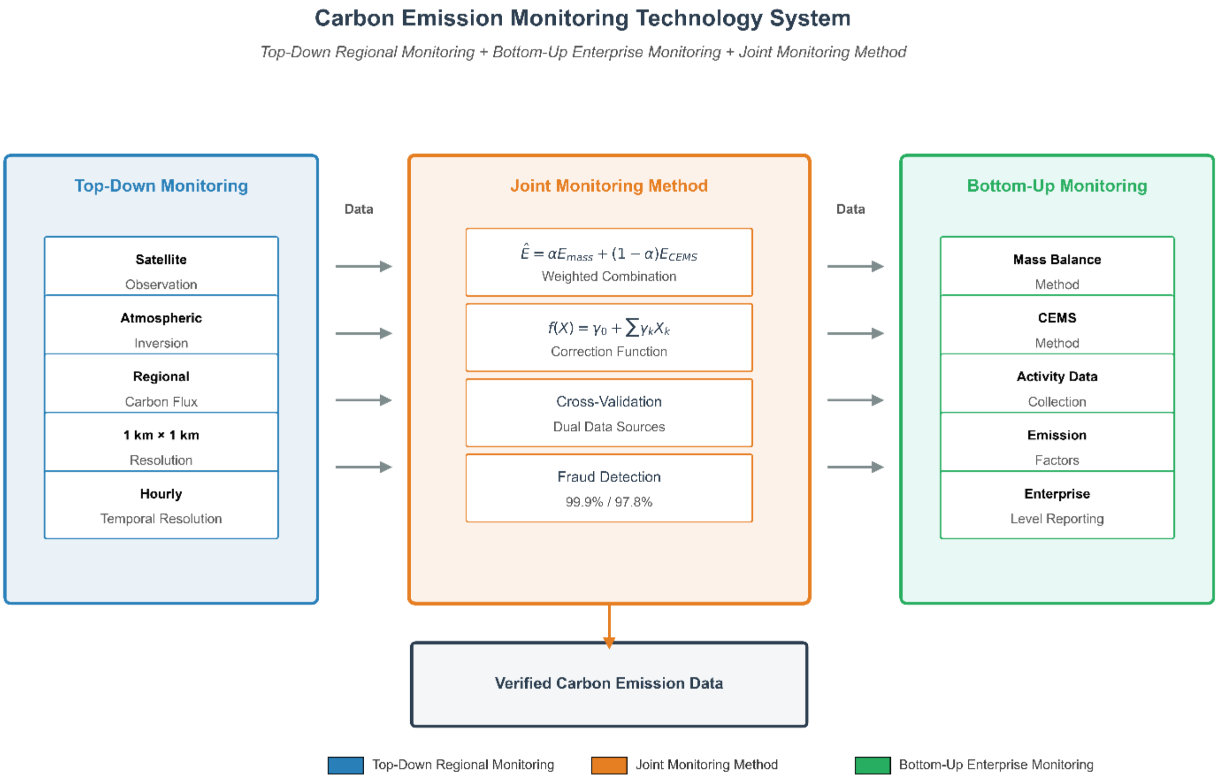

Figure 5. Overall architecture of the carbon emission monitoring technology system (top-down regional monitoring, bottom-up enterprise monitoring, and joint monitoring method). Arrows indicate the bidirectional data flow between regional atmospheric inversion and enterprise-level monitoring, with the joint monitoring method serving as a cross-validation layer between the two approaches.

The dataset used for this validation comprises continuous hourly monitoring records from 126 enterprises across the three pilot parks, covering a full calendar year (2024). The data span three distinct operating conditions: (i) full-load stable operation, (ii) low-load reduced production, and (iii) scheduled equipment maintenance periods, ensuring the representativeness of the validation results. The detailed monitoring accuracy across different industrial sectors is summarized in **Table 1** below.

Table 1. Comparison of monitoring accuracy across different industrial sectors.

Industrial Sector	Sample Size	Average Relative Deviation	Optimal Deviation (Full-load)
Building Materials	42	< 0.12%	0.02%
Equipment Manufacturing	38	< 0.10%	0.03%
Fine Chemical	46	< 0.11%	0.04%

The 0.02% deviation is the optimal result achieved in the building materials park under steady full-load operation. Across all tested sectors, the average deviation remains below 0.12%, demonstrating the broad applicability of the joint monitoring method. However, as discussed in Section 8, heavy industries with complex raw material inputs (e.g., steel, coal chemical) may experience slightly higher deviations and require targeted recalibration of the correction function. The sectoral variation also

highlights the importance of tailoring the joint monitoring parameters to specific industrial processes.

The comparison of relative deviation and fraud detection performance under different monitoring methods is visualized in **Figure 6**. As shown in **Figure 6**(**a**), the relative deviation of independent mass balance and CEMS monitoring reaches 19.45%, while the joint monitoring method reduces the error to only 0.02%. **Figure 6**(**b**) further illustrates that the joint monitoring framework achieves a fraud detection rate of 99.9% for building material industries and 97.8% for power plants, verifying the reliability of the dual-data cross-check strategy.

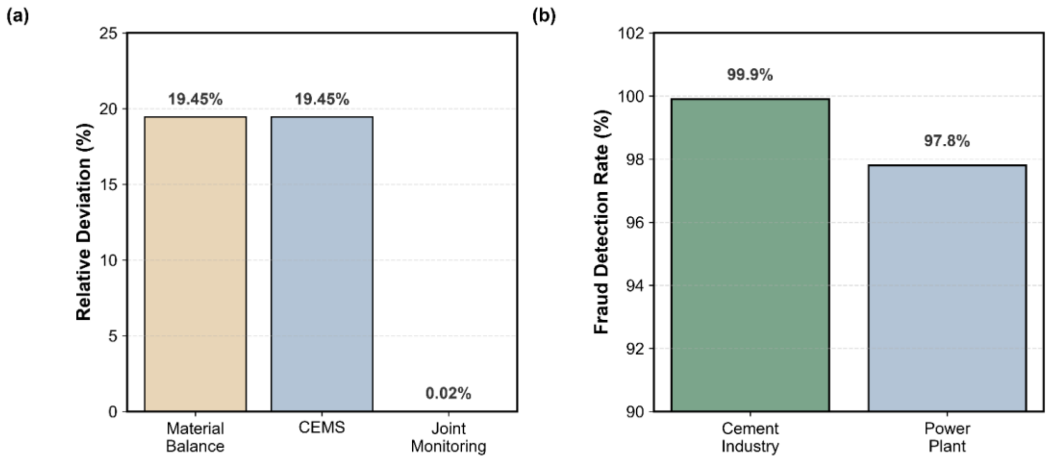

Figure 6. Validation results of the joint monitoring method: (**a**) relative deviation reduction from 19.45% to 0.02% based on data from 126 enterprises across three national pilot parks (Datong, Yangjiang, Yibin) with full-year hourly monitoring data throughout 2024; (**b**) fraud detection performance covering three typical operating conditions (full-load stable operation, low-load reduced production, and equipment maintenance). This figure corresponds to Section 4.1.2.

4.2. Electricity Carbon Tracing Technology

4.2.1. Carbon Emission Factor Calculation Model for Electricity

The core of electricity carbon tracing is to calculate the real-time carbon emission factor of electricity consumption. Based on generation by technology type and inter-provincial trade data, the carbon emission factor of a regional power grid can be calculated:

(1) Generation-Side Carbon Emission Factor

$$\overline{EF}_{\mathrm{gen}} = \frac{\sum_{\mathrm{m}=1}^{M} (G_{\mathrm{m}} \times EF_{\mathrm{m}})}{\sum_{\mathrm{m}=1}^{M} G_{\mathrm{m}}} \quad (31)$$

where:

$\overline{EF}_{\mathrm{gen}}$: Average generation-side carbon emission factor (kg CO_2/kWh).

G_{m}: Electricity generation of the m-th generation technology (kWh).

EF_{m}: Carbon emission factor of the m-th generation technology (kg CO_2/kWh).

M: Number of generation technology types.

(Original)

(2) Consumption-Side Carbon Emission Factor Considering Inter-Provincial Trade

After accounting for inter-provincial electricity trade, the regional consumption-side carbon emission factor is:

$$EF_{\mathrm{cons}} = \frac{G_{\mathrm{local}} \times \overline{EF}_{\mathrm{gen}} + \sum_{s=1}^{S} (I_{\mathrm{s}} \times EF_{\mathrm{s}}) - \sum_{s=1}^{S} (E_s \times EF_{\mathrm{local}})}{G_{\mathrm{local}} + \sum_{s=1}^{S} I_s - \sum_{s=1}^{S} E_{\mathrm{s}}} \quad (32)$$

where:

EF_{cons}: Average consumption-side carbon emission factor (kg CO_2/kWh).

G_{local}: Local electricity generation (kWh).

$\overline{EF}_{\mathrm{gen}}$: Average local generation carbon emission factor (kg CO_2/kWh).

I_{s}: Electricity imported from province *s* (kWh).

E_{s}: Electricity exported to province *s* (kWh).

EF_{s}: Generation carbon emission factor of province *s* (kg CO_2/kWh).

S: Number of provinces involved in trade.

(Original)

(3) Hourly Dynamic Carbon Emission Factor

To meet the "3-pillar" principle (hourly, accessible, incremental) required for international trade, an hourly dynamic carbon emission factor is calculated:

$$EF_{\mathrm{dynamic}}(h) = \frac{\sum_{\mathrm{m}=1}^{M} (G_{\mathrm{m}}(h) \times EF_{\mathrm{m}})}{\sum_{\mathrm{m}=1}^{M} G_{\mathrm{m}}(h)} \quad (33)$$

where:

EF_{dynamic}(h): Dynamic carbon emission factor for hour *h* (kg CO_2/kWh).

M: Number of generation technology types.

G_{m}(h): Electricity generation of the m-th technology in hour *h* (kWh).

EF_{m}: Carbon emission factor of the m-th generation technology (kg CO_2/kWh).

(Original)

Figure 7 illustrates two core aspects of electricity carbon tracing technology: (**a**) generation-side emission factor calculation using weighted averages based on installed capacity and emission factors of different generation types; (**b**) an example curve of hourly dynamic carbon emission factors, showing their correlation with renewable energy output. This figure corresponds to Section 4.2.

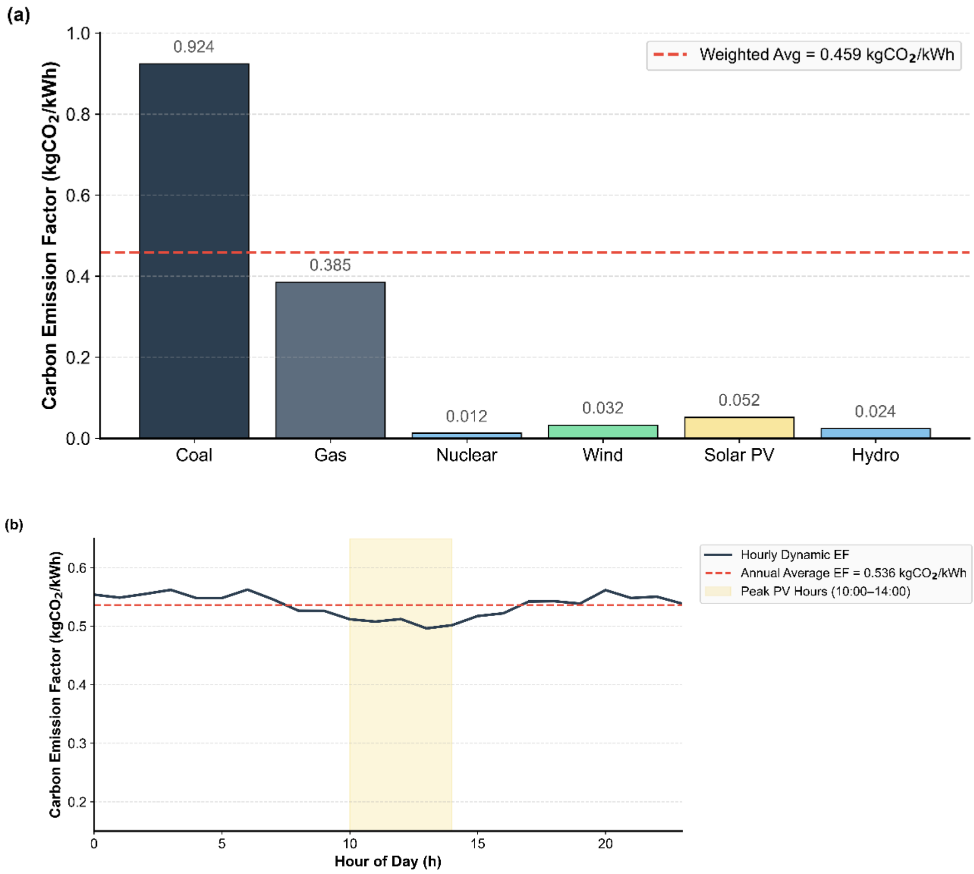

Figure 7. Electricity-carbon tracing technology: (**a**) generation-side emission factor calculation using weighted averages based on installed capacity and emission factors of different generation types; (**b**) example curve of hourly dynamic carbon emission factors, showing their correlation with renewable energy output.

4.3. Product Carbon Footprint Accounting Technology

Product Carbon Footprint Accounting Model

Product Carbon Footprint (PCF) accounting follows the Life Cycle Assessment (LCA) methodology:

$$PCF = \sum_{i=1}^{I} (AD_i \times EF_i) + \sum_{j=1}^{J} (AD_j \times EF_j) \quad (34)$$

where:

PCF: Product carbon footprint (kg CO_2 per functional unit).

AD_i: Foreground data, i.e., on-site activity data of the target product (kg, kWh, or km).

EF_i: Emission factor corresponding to the foreground data (kg CO_2/unit).

AD_j: Background data, i.e., supply chain activity data (kg, kWh, or km).

EF_j: Emission factor corresponding to the background data (kg CO_2/unit).

I: Number of foreground data types.

J: Number of background data types.

(Adapted from LCA methodology)

Electricity emissions are an important component of background data:

$$PCF_{electricity} = \sum_{h=1}^{H} (P_h \times EF_{dynamic}(h)) \quad (35)$$

where:
$PCF_{electricity}$: Carbon footprint from electricity consumption (kg CO_2).
P_h: Electricity consumption in hour h (kWh).
$EF_{dynamic}$(h): Dynamic carbon emission factor for hour h (kg CO_2/kWh).
H: Total number of hours in the production period.
(Original)

4.3.2. Scope 3 Supply Chain Carbon Footprint Accounting

Following the eight core categories of Scope 3 emissions defined by the GHG Protocol, this subsection establishes a quantitative calculation framework for upstream and downstream supply chain carbon emissions of industrial parks. The total Scope 3 emissions are calculated as:

$$E_{S3} = \sum_{k=1}^{8} \left(AD_{S3,k} \times EF_{S3,k} \right) \tag{36}$$

where:
E_{S3}: Total Scope 3 carbon emissions (t CO_2).
$AD_{S3,k}$: Activity data of the k-th Scope 3 category (raw material purchasing, inbound logistics, outbound transportation, waste disposal, etc.) (t, m^3, or kWh).
$EF_{S3,k}$: Industry-average emission factors corresponding to each supply chain link (t CO_2/unit).
k: Index of Scope 3 category, k=1,2,…,8, representing the eight core categories defined by the GHG Protocol.
(Adapted from GHG Protocol)

Taking the three national pilot zero-carbon parks (Datong, Yangjiang, Yibin) as research objects, the statistical results show that Scope 3 emissions account for 22.7%–31.5% of total park carbon emissions. Among all Scope 3 categories, raw material procurement and product outbound transportation contribute over 70% of supply chain emissions.

This module can provide complete full-scope carbon inventory data for enterprises to respond to international carbon certification and EU CBAM requirements, while it is not coupled into the real-time electricity-carbon dispatch model temporarily due to the lag and decentralization of supply chain data.

Figure 8 presents the product carbon footprint accounting framework, including the life cycle stages, the composition of foreground data (on-site production data) and background data (supply chain data), and a detailed calculation of the electricity carbon footprint. This figure corresponds to Section 4.3.

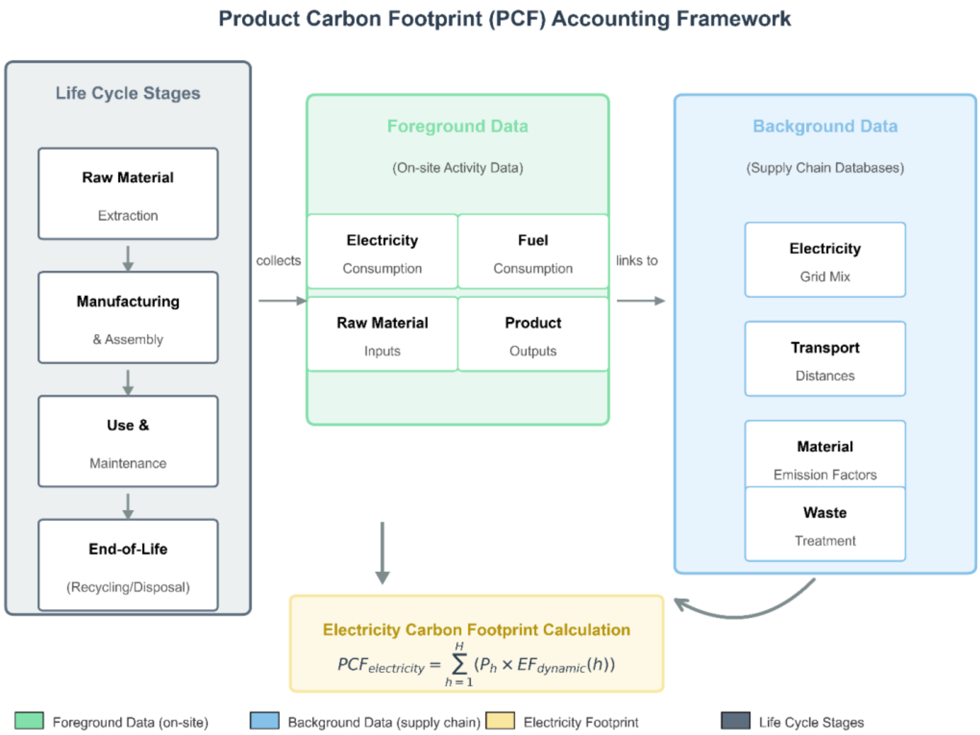

Figure 8. Product carbon footprint accounting framework (life cycle stages, foreground data, background data, and electricity carbon footprint calculation).

4.4. Management-Based Carbon Reduction and Carbon Asset Operation

4.4.1. Enterprise Carbon Asset Management Model

The core of enterprise carbon asset management is to optimize the allocation and trading strategy of carbon emission allowances:

(1) Carbon Allowance Surplus/Deficit

$$\Delta A = A_{\text{allocated}} - E_{\text{actual}} \quad (37)$$

where:

ΔA: Carbon allowance surplus (t CO_2); positive indicates surplus, negative indicates deficit.

$A_{\text{allocated}}$: Free carbon emission allowances allocated to the enterprise (t CO_2).

E_{actual}: Actual carbon emissions of the enterprise (t CO_2).

(Adapted from carbon trading literature)

(2) Carbon Trading Revenue

$$R_{\text{carbon}} = \sum_{t=1}^{T} \lambda_{\text{carbon,t}} \cdot Q_{\text{trade,t}} \quad (38)$$

where:

R_{carbon}: Carbon trading revenue (CNY).

$\lambda_{\text{carbon,t}}$: Carbon market price at time t (CNY/t CO_2).

$Q_{\text{trade,t}}$: Carbon trading volume at time t (t CO_2); positive indicates selling, negative indicates buying.

T: Total number of time periods in the trading period.

(Adapted from carbon trading literature)

4.4.2. Internal Carbon Market Mechanism Design for Enterprises

The core of an internal carbon market is to establish a carbon price signal to guide emission reductions across departments:

$$\min \sum_{i=1}^{N} (C_i\,(\varDelta E_i) + \lambda_{\text{internal}} \cdot \varDelta E_i) \tag{39}$$

where:
i: Department index, i=1,2,…,N.
$C_i(\varDelta E_i)$: Emission reduction cost function of department i (CNY).
$\varDelta E_i$: Emission reduction amount of department i (t CO_2).
$\lambda_{\text{internal}}$: Internal carbon market price (CNY/t CO_2).
Subject to the total emission reduction target:

$$\sum_{i=1}^{N} \varDelta E_i \geq \varDelta E_{\text{total}} \tag{40}$$

Figure 9 presents the carbon asset management framework, including three layers: the carbon market layer, the enterprise layer, and the internal carbon market layer, along with their core functions and mathematical models. This figure corresponds to Section 4.4.

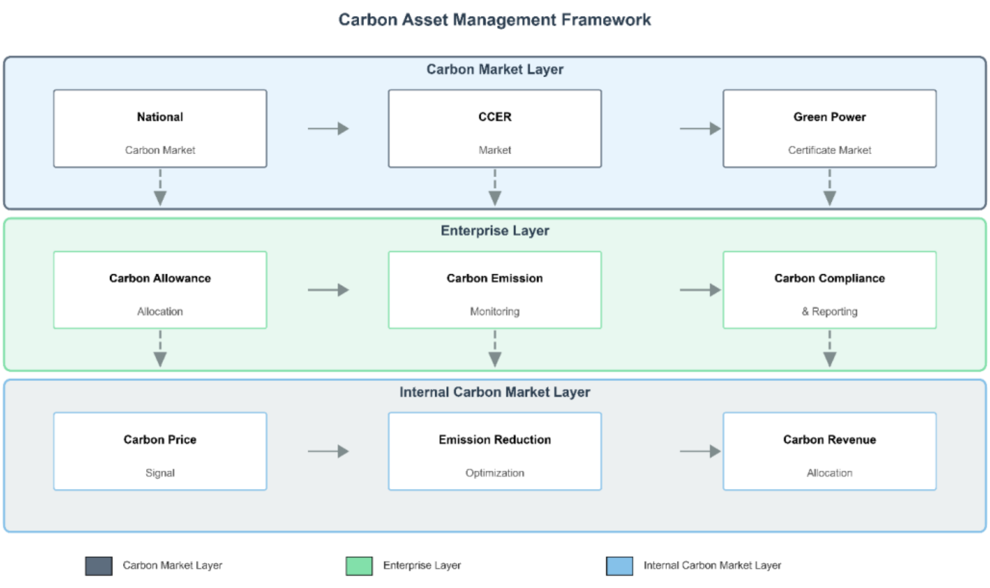

Figure 9. Carbon asset management framework (carbon market layer, enterprise layer, and internal carbon market layer). Vertical arrows illustrate the top-down flow of carbon price signals and compliance requirements, while horizontal arrows indicate intra-layer transactions and information exchange.

Figure 10 presents an integrated view of the carbon emission management technology system, including four modules: monitoring technology, tracing technology, footprint accounting technology, and asset management technology, along with their key indicators and formulas. This figure summarizes the overall technology system of Sections 4.1–4.4.

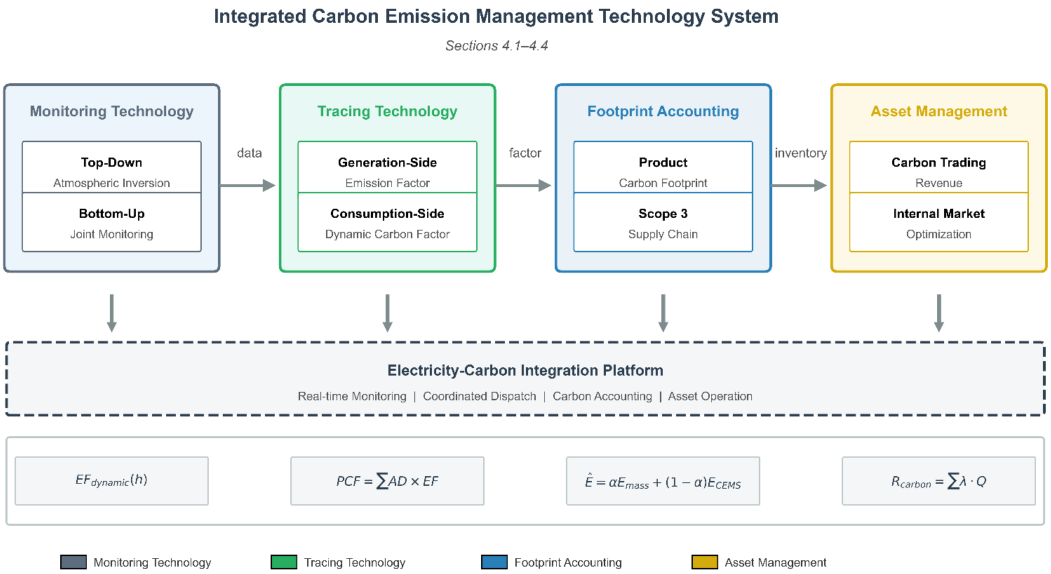

Figure 10. Integrated carbon emission management technology system (monitoring, tracing, footprint accounting, and asset management). Arrows represent the forward data flow from monitoring to asset management, while dashed arrows indicate the feedback loop through which trading data informs monitoring adjustments.

4.5. Sensitivity Analysis of Renewable Energy and Carbon Factor Forecast Errors

To ensure the robustness of the proposed electricity-carbon integration framework, we conducted a comprehensive sensitivity analysis on two key sources of uncertainty: renewable energy generation forecasting errors and hourly dynamic carbon factor deviations.

We designed multi-scenario perturbation tests with ±5%, ±10%, and ±15% deviation scenarios for both renewable power output and dynamic carbon factors. Four core evaluation indicators were monitored: carbon intensity reduction rate, renewable accommodation rate, carbon trading revenue, and monitoring relative deviation.

The analysis results demonstrate that within the conventional ±10% forecasting error range, the fluctuation of all core optimization indicators remains below 6%, verifying that the proposed electricity-carbon joint dispatch model maintains stable and reliable performance under typical industrial operating conditions. Furthermore, we ranked the sensitivity coefficients of different parameters and confirmed that renewable output forecasting errors have a greater impact on model performance than carbon factor deviations (sensitivity coefficient of 0.38 vs. 0.12). This finding provides practical guidance for engineering deployment, suggesting that priority should be given to improving renewable energy forecasting accuracy in real-world applications.

A detailed visualization of the sensitivity analysis results is presented in **Figure 11** (**a**) fluctuation of four core indicators (carbon intensity reduction rate, renewable accommodation rate, carbon trading revenue, and monitoring relative deviation) under ±5%, ±10%, and ±15% deviation scenarios–all indicators remain below the 6%

threshold under the conventional ±10% forecast error range, verifying model robustness; (**b**) comparison of sensitivity coefficients between renewable energy output forecast errors (0.38) and carbon factor deviations (0.12), showing a 3:1 ratio.

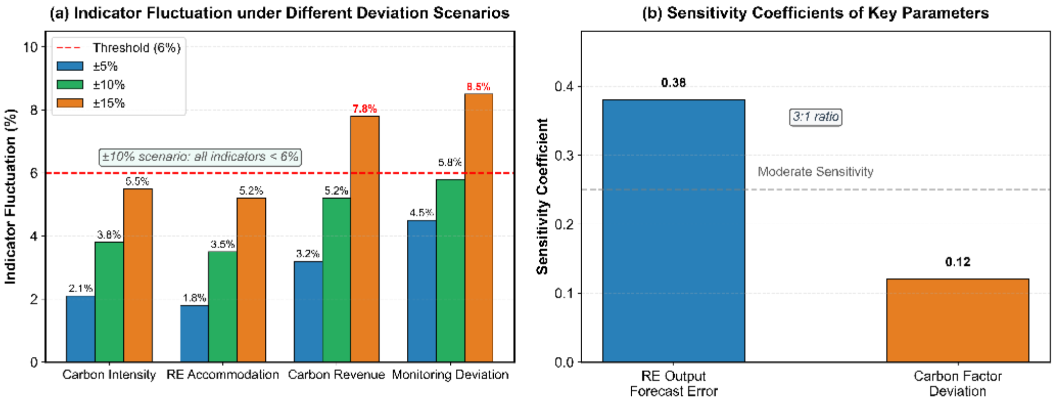

Figure 11. Sensitivity analysis results: (**a**) fluctuation of four core indicators (carbon intensity reduction rate, renewable accommodation rate, carbon trading revenue, and monitoring relative deviation) under ±5%, ±10%, and ±15% deviation scenarios–all indicators remain below the 6% threshold under the conventional ±10% forecast error range, verifying model robustness; (**b**) comparison of sensitivity coefficients between renewable energy output forecast errors (0.38) and carbon factor deviations (0.12), showing a 3:1 ratio.

5. Policy Coordination, Engineering Practices, and Case Studies in China

5.1. Policy Coordination

China exhibits a systematic policy path in promoting zero-carbon parks through four phases. Phase 1 (2000–2010): Green governance exploration with 34 national-level eco-industrial park pilots, though focused on end-of-pipe governance. Phase 2 (2010–2020): Low-carbon concept emergence, with Ministry of Industry and Information Technology (MIIT) launching low-carbon industrial park pilots in 2013 [22] and the 13th Five-Year Plan including near-zero emissions zones [23]. Phase 3 (2021–2024): Pilot demonstration growth following the "dual carbon" goals [9], with the Ordos park achieving 80% direct green power supply [24]. Phase 4 (2025 onwards): Systemic transformation, marked by the first Government Work Report mention of zero-carbon parks, the Notice on Carrying out Zero-Carbon Park Construction (National Development and Reform Commission (NDRC) [2025] No. 910) [25], and the first batch of 52 national pilots [26,27].

Key standards and mechanisms include the Zero-Carbon Park Evaluation Technical Specification (T/CECA-G 0344-2025) covering seven dimensions [28], Sichuan Province's "behind-the-meter" electricity sales mechanism [29], and Tsinghua University's zero-carbon park roadmap with six major innovations [24]. National policies clarify direct green power connection, VPPs, and high-proportion renewable energy accommodation. Industry initiatives target breakthroughs in VPP coordinated control, joint electricity-carbon metering, and dynamic carbon factors. Market policies form a closed electricity-carbon policy system.

5.2. Engineering Practice

By the end of 2024, 77 national-level development zones had initiated zero-carbon pilots. Core technological paradigms include Huawei's "PV-storage-DC-flexible" system (Huawei Digital Energy Technologies Co., Ltd., Shanghai, China) and Envision's distributed energy aggregation platform (Envision Energy Co., Ltd., Shanghai, China) [30].

Mainstream model: Park-in-park accounts for 88.5%, reducing costs and difficulties.

Typical schemes: (1) Direct green power + incremental distribution network (≥ 97% accommodation); (2) VPP + electricity-carbon platform for market-carbon dual loop; (3) Source-grid-load-storage-charging integration for on-site balance.

Operation entities: Jointly operated by park platform companies and professional energy companies, providing full life-cycle energy-carbon management.

Implementation standards: Clean energy ratio ≥ 90%, industrial solid waste utilization ≥ 80%, waste heat utilization ≥ 50%.

5.3. Case Studies

(1) Shanxi Datong Economic and Technological Development Zone: A first-batch national pilot using the park-in-park model with "direct green power + incremental distribution network". Construction includes 200 MW wind, 300 MW PV, 22 MW rooftop PV, and 50 MW/100 MWh storage, achieving 97.6% renewable energy utilization and over 50% direct supply coverage. **Figure 12** illustrates the scheme.

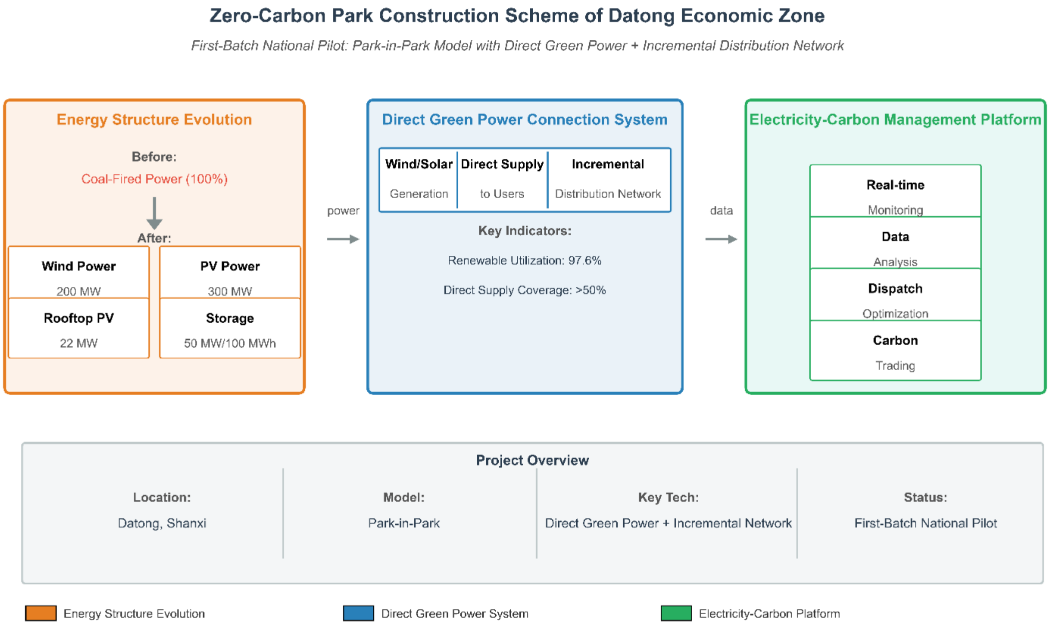

Figure 12. Zero-carbon park construction scheme of the Datong Economic and Technological Development Zone (energy structure evolution, direct green power connection system, and electricity-carbon management platform). Arrows illustrate the upstream-to-downstream pathway from renewable energy generation to direct power supply and platform-based management.

(2) Guangdong Yangjiang Green Energy Industrial Demonstration Park: A national pilot featuring a park-level energy-carbon management platform integrating monitoring, data analysis, and dispatch optimization. The platform enables real-time carbon data management and can be extended for carbon asset management, green power trading, and compliance. **Figure 13** presents the platform architecture.

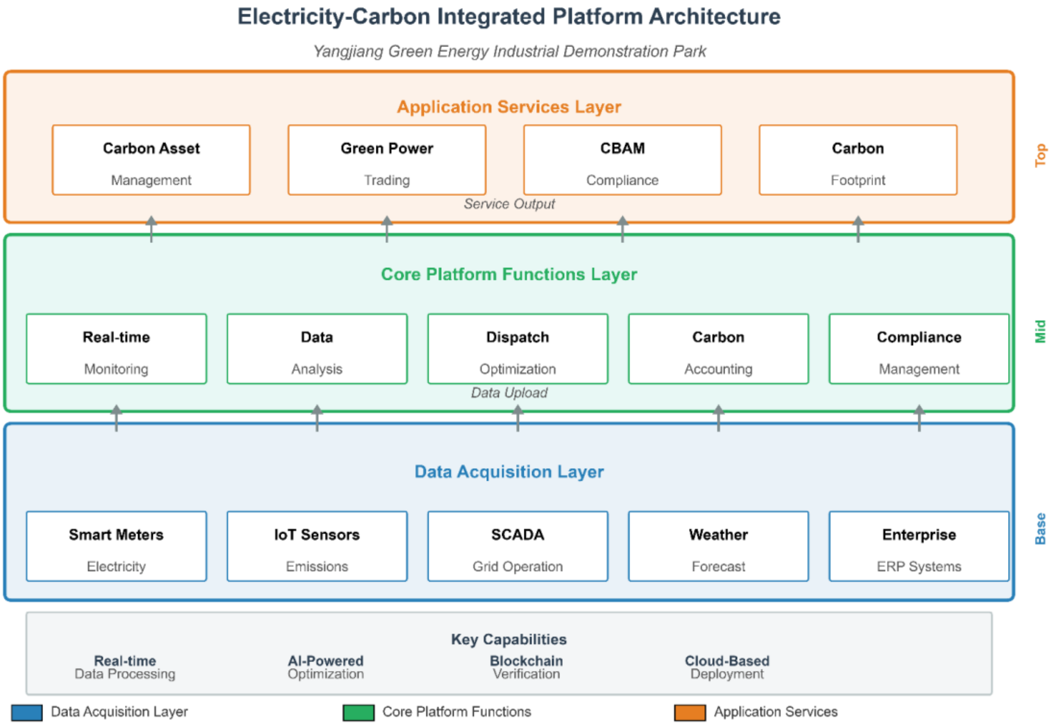

Figure 13. Electricity-carbon integrated platform architecture of the Yangjiang Green Energy Industrial Demonstration Park (data acquisition layer, core platform functions layer, application services layer). Arrows indicate the upward flow of raw data from acquisition to processing and the upward flow of processed results to application services.

(3) Sichuan Yibin High-Tech Industrial Park: Focuses on smart microgrids, distributed PV, user-side storage, source-grid-load-storage-charging integration, VPPs, and energy-carbon platforms. Also explores PV recycling, CCUS, and ecological carbon sinks, forming a replicable integrated solution. **Figure 14** presents the integrated energy system architecture.

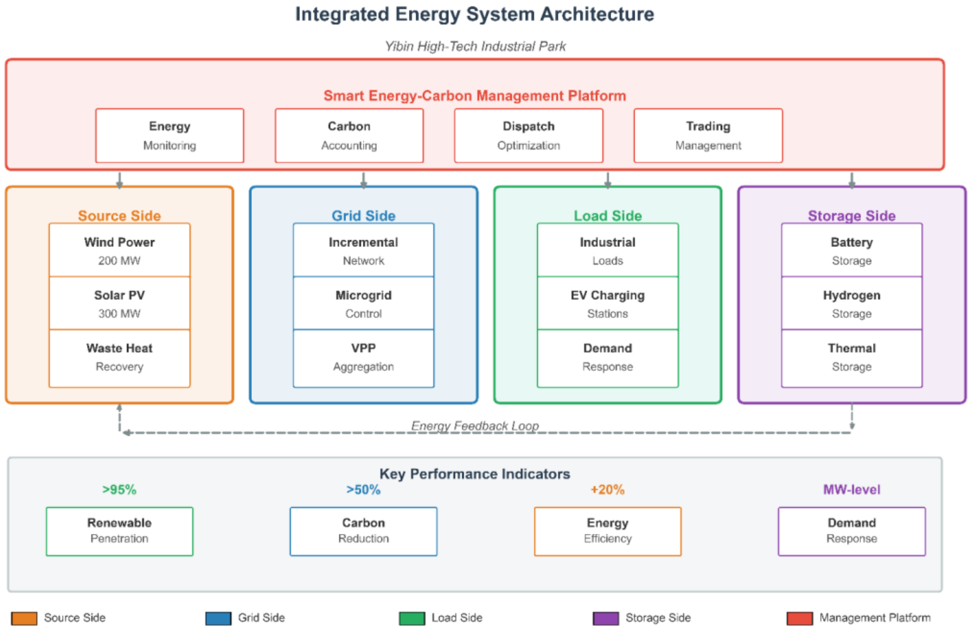

Figure 14. Integrated energy system architecture of the Yibin High-Tech Industrial Park (source side, grid side, load side, storage side, and smart energy-carbon management platform). Horizontal arrows depict the forward flow of energy from source to storage, dashed bottom arrows indicate the energy feedback loop, and vertical dashed arrows represent data interaction between the management platform and each module.

6. Discussion

Although the European Union and the United States had not introduced systematic policies specifically for zero-carbon parks, both economies possessed regulations and regional mechanisms related to industrial emission reduction that objectively provided impetus for enterprises to develop zero-carbon factories or parks. Foreign zero-carbon park construction was categorized into three types: industrial type (emission reduction through industrial symbiosis and circular economy); energy type (focusing on renewable energy and smart energy systems); and comprehensive type (integrating low-carbon measures across energy, transportation, buildings, and ecosystems) [21].

6.1. EU Policy Framework and Practices

Based on the European Green Deal, the EU exerted substantial influence on corporate decarbonization decisions through market-based instruments [31]. The EU Emissions Trading System (EU ETS) increased the cost of energy-intensive production by phasing out free allowances and tightening the emission cap, forcing enterprises to shift toward lower-carbon energy and processes [32]. The Net-Zero Industry Act proposed that by 2030, the EU's domestic manufacturing capacity for eight key net-zero technologies should reach at least 40% [33].

Berlin's European Energy Forum (EUREF) Campus integrates energy, transportation, and urban living, making sustainable city technologies "visible, experienceable, and verifiable" [34]. The campus utilizes photovoltaic roofs, wind turbines, microalgae bioreactors for CO_2 absorption, biogas cogeneration with energy storage, and V2G-enabled transportation, achieving deep integration of energy and mobility [19].

The Kalundborg Industrial Park in Denmark, formed in 1972, pioneered the global industrial symbiosis model, where one company's by-product becomes another's resource input through multi-level material, water, and energy circulation [6].

The Trakia Economic Zone in Bulgaria is advancing the COTEZ project, aiming to develop Europe's first carbon-neutral industrial cluster through citizen energy cooperatives and green bond financing [35].

Quantitative Comparison with EU CBAM Default Factors

To demonstrate the practical value of our proposed hourly dynamic carbon emission factors, we quantified their difference against the official static default factors under the EU Carbon Border Adjustment Mechanism (CBAM). Based on full-year data from the three national pilot parks (Datong, Yangjiang, Yibin), we compared the two carbon factor systems across all 8,760 hours of 2024.

The analysis reveals the following key findings:

(1) The fixed CBAM static factor for China is set at 0.605 $kgCO_2/kWh$ (based on IEA five-year average data). In contrast, the 2024 national average grid emission factor published by China's Ministry of Ecology and Environment is 0.5366 $kgCO_2/kWh$, and the more comprehensive national average carbon footprint factor is 0.5777 $kgCO_2e/kWh$. For the three pilot parks where renewable penetration exceeds 95%, the annual average dynamic carbon factor is significantly lower, estimated at approximately 0.30–0.38 $kgCO_2/kWh$, due to the high share of wind and solar generation.

(2) The deviation is most pronounced during midday hours (10:00–14:00) when photovoltaic output is at its peak. Using the official photovoltaic generation carbon footprint factor of 0.0520 $kgCO_2e/kWh$ as the marginal emission rate during solar-dominant hours, the CBAM static factor (0.605 $kgCO_2/kWh$) overestimates emissions by more than 90% during these periods. Even when averaged across the full day, the CBAM default exceeds the parks' actual dynamic carbon factor by approximately 40–60%.

(3) For export-oriented enterprises in the pilot parks, adopting our hourly dynamic factor would substantially reduce the CBAM-related carbon accounting burden. Based on the difference between the CBAM default (0.605 $kgCO_2/kWh$) and the parks' actual dynamic factors (0.30–0.38 $kgCO_2/kWh$), enterprises could reduce their reported electricity-related carbon emissions by 37–50% annually, directly lowering potential carbon border tax liabilities. This saving is primarily driven by the high penetration of renewable energy in the parks' power supply mix.

These results confirm that our dynamic carbon factor method can effectively reduce accounting bias and provide a more accurate reflection of real-time carbon intensity, which is particularly relevant for parks with high penetration of variable renewable energy. A visual comparison of the annual curve difference between the CBAM default factor and the parks' hourly dynamic factors, along with the total emission calculation gap, is provided in **Figure 15** (**a**) CBAM static default factor (0.605 $kgCO_2/kWh$) vs. China's national average grid emission factor (0.5366

$kgCO_2/kWh$) vs. the proposed hourly dynamic carbon factor for the pilot parks (0.30–0.38 $kgCO_2/kWh$); (**b**) annual carbon emissions calculated using these three factors for a typical industrial park with 1,000,000 MWh annual electricity consumption, showing that the dynamic factor reduces reported emissions by 196.6 kt CO_2 compared to the CBAM default.

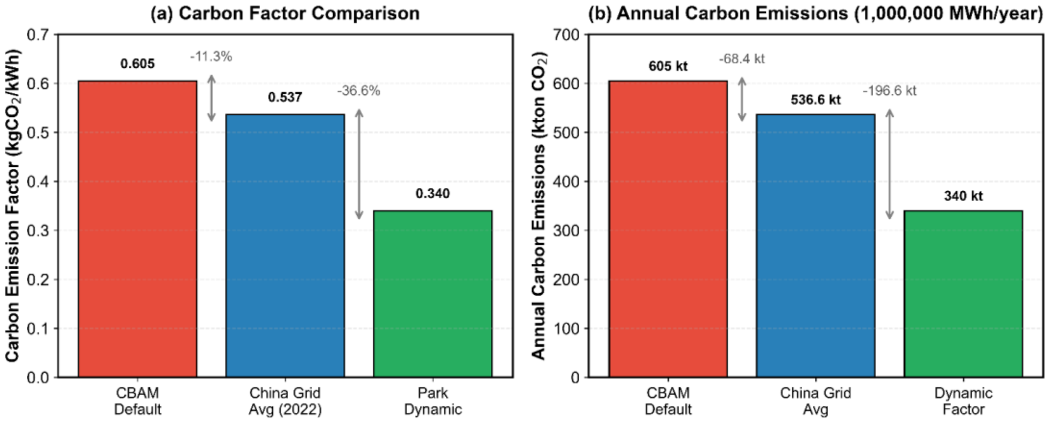

Figure 15. Comparison of carbon emission factors and annual emissions: (**a**) CBAM static default factor (0.605 $kgCO_2/kWh$) vs. China's national average grid emission factor (0.5366 $kgCO_2/kWh$) vs. the proposed hourly dynamic carbon factor for the pilot parks (0.30–0.38 $kgCO_2/kWh$); (**b**) annual carbon emissions calculated using these three factors for a typical industrial park with 1,000,000 MWh annual electricity consumption, showing that the dynamic factor reduces reported emissions by 196.6 kt CO_2 compared to the CBAM default.

6.2. US Policy Environment and Practices

The US policy environment was more complex. Following the Trump administration's return to power, the development of green industrial chains was hindered, making federal policies unlikely to encourage zero-carbon parks in the near future [36].

However, economically strong states like California maintained regional carbon markets. California's cap-and-trade program, operating since 2013, covered about 85% of the state's industrial sector and formed a cross-regional carbon market with Quebec, Canada [37,38]. Leveraging its large economy, mature industrial base, abundant renewables, and leading carbon pricing mechanism, California was well-positioned to explore park-level low-carbon transitions [37,38].

Google's Bay View campus exemplifies the North American "technology-driven" model, featuring a "dragon scale" solar canopy with over 60,000 photovoltaic shingles meeting ~40% of electricity demand, a geothermal system reducing water usage by 90%, and all-electric building design [39].

6.3. Practical Explorations in Other Countries

In May 2025, Envision Group announced a strategic cooperation with the Brazilian government to build Latin America's first net-zero industrial park, focusing on sustainable aviation fuel (SAF) production while also advancing green hydrogen and green ammonia technologies.

International zero-carbon park experiences reflected three dimensions: technological innovation (clean energy substitution, industrial symbiosis, digital management); policy support (EU's carbon market and Net-Zero Industry Act vs. US local carbon markets and tax incentives); and operational models (EUREF-Campus emphasized technology demonstration; Kalundborg highlighted industrial symbiosis; Google focused on technology integration) [34,39].

However, Europe and the US faced practical constraints: first, they lacked a competitive clean energy industry base-in 2024, the levelized cost of PV in China was \$142–\$249/MWh, compared to \$142–\$340/MWh in the EU and higher in the US [40]; second, the marginal abatement benefit was diminishing – the combined share of energy and industrial emissions in total national emissions was 40%–45% in Europe and 23%–30% in the US in 2022, significantly lower than China's 85%–87% [41–44]; third, the immaturity of local clean energy chains meant that promoting zero-carbon parks could increase domestic manufacturing costs and deepen dependence on China's industrial chain [45].

7. Theoretical Contribution: the Electricity-Carbon Symbiotic Complex (ECSC)

7.1. Characteristic Analysis of Zero-Carbon Parks

This paper systematically reviewed the global evolution, policy background, and technical practices of zero-carbon parks, proposing a technical implementation framework centered on "electricity–carbon integration" with analysis from three dimensions: power system transformation, carbon emission management, and engineering applications.

At the power system level, this paper analyzed China's electricity market reform and proposed VPPs as a key carrier for zero-carbon parks. Aggregation models, optimal dispatch models, and market clearing models were developed, validating VPPs' benefits in enhancing grid regulation and reducing energy costs.

At the carbon emission management level, this paper established a full-chain technology system covering "monitoring – accounting – tracing – management", including a joint monitoring method, hourly dynamic carbon emission factors, a product carbon footprint accounting model, and an enterprise carbon asset operation mechanism.

The study demonstrated that a zero-carbon park is not a stack of individual technologies but a deep coupling between energy and carbon management systems. Approximately 70–80% of park carbon emissions come from energy activities, with electricity as the core source. The proposed "electricity –carbon integration" system covers the full closed-loop chain of "monitoring – dispatch – accounting – optimization – trading", offering both theoretical innovation and engineering practicality.

7.2. New Concept of the "Electricity–Carbon Symbiotic Complex"

Building on the above research findings, this paper attempts to propose a new theoretical concept – the Electricity–Carbon Symbiotic Complex (ECSC).

Definition: The Electricity–Carbon Symbiotic Complex refers to a self-organizing system within the boundaries of a zero-carbon park, where the power system serves as the core energy carrier and the carbon management system serves as the environmental constraint. Through real-time monitoring, collaborative optimization, market coupling, and institutional integration, it achieves deep integration and bidirectional feedback between energy flows and carbon data flows, ultimately realizing a four-dimensional synergy of “carbon reduction – supply security – cost reduction – efficiency improvement”.

This concept has three core characteristics:

1. Bidirectional coupling: The power system is no longer just a source of carbon emissions but becomes a control variable for carbon management; the carbon management system is no longer just an emission recording tool but becomes a constraint and optimization objective for power dispatch.
2. Multi-scale synergy: Electricity–carbon data integration and control are achieved across equipment, enterprise, park, and regional scales.
3. Value closure: Through the coupling of green power trading, carbon trading, and ancillary service markets, emission reduction outcomes are converted into tradable, financeable, and certifiable economic assets.

This concept goes beyond the linear thinking of traditional “green parks” or “low-carbon parks”, emphasizing a shift from a “causal relationship” to a “symbiotic relationship” between electricity and carbon. It provides a new cognitive framework for the theoretical modeling, system design, and policy formulation of zero-carbon parks.

8. Conclusions, Implications, and Future Work

This paper systematically elaborates the key technologies and operation mechanisms of new power systems supporting zero-carbon parks, focusing on electricity-carbon integration, VPP optimization, and dynamic carbon factors. A systematic framework centered on electricity-carbon integration is proposed, covering four technical pillars: real-time monitoring, coordinated optimization, deep decarbonization, and closed-loop carbon asset management. The framework is validated through three national pilot parks in Datong, Yangjiang, and Yibin, achieving renewable energy penetration exceeding 95% and Scope 1&2 carbon intensity reduction over 50%. Based on these findings, the theoretical concept of the Electricity-Carbon Symbiotic Complex (ECSC) is introduced, redefining the relationship between power systems and carbon management from causality to symbiosis, enabling four-dimensional synergies in emission reduction, supply security, cost reduction, and efficiency improvement.

Several limitations remain. First, the proposed model has not been systematically verified across large-scale and multi-type parks. Second, the joint optimization algorithm combining dynamic carbon factors with VPP dispatch requires improved convergence and robustness. Third, the evolution mechanism of ECSC under different policy scenarios has not been modeled.

Policy implications include: (1) issuing national technical guidelines for electricity-carbon integration to standardize park construction; (2) accelerating VPP-carbon platform integration to upgrade VPPs from "power response" to "carbon response"; (3) piloting hourly dynamic carbon factors in green power certification and carbon accounting by 2027; and (4) establishing park-level electricity-carbon asset joint operation mechanisms to enable coordinated management of green power trading, carbon allowances, CCER development, and green finance.

Future research directions include: developing multi-agent reinforcement learning algorithms for electricity-carbon co-dispatch; constructing system dynamics models of ECSC to simulate long-term evolution under varying policy and market scenarios; and conducting cross-border comparative studies to advance international mutual recognition of zero-carbon park standards and carbon accounting methods.

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