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Research on Planning Path of Comprehensive Energy System in Zero-carbon Park: Theoretical Framework and Systematic Method

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Abstract: Under China's "dual carbon" goals, zero-carbon industrial parks serve as critical platforms for urban carbon reduction, with integrated energy system planning being the cornerstone of decarbonization. This study establishes a universal planning framework that first characterizes zero-carbon parks as complex adaptive systems featuring multi-energy coupling, source-grid-load-storage interaction, and carbon-energy synergy. The research proposes a three-phase systematic planning approach- "baseline diagnosis, multi-objective optimization, and dynamic implementation" -which builds an intelligent system integrating electricity, heat, cooling, and hydrogen through carbon-energy and multi-energy flow analysis, supported by digital twin technology and multi-objective algorithms. The study also identifies implementation challenges including system stability, institutional costs, and economic risks, proposing solutions at the institutional, standard, and technical levels. This methodology aims to provide customizable theoretical tools and practical guidance for various parks, facilitating the transition from experience-driven to science-based planning in zero-carbon industrial parks.

Keywords: zero-carbon park; integrated energy system; planning path; multi-objective optimization; carbon-energy flow synergy; digital twin

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1. Introduction

The deepening of global climate governance has made deep decarbonization of energy systems an irreversible strategic imperative. As hubs for industrial clusters and carbon emissions, industrial parks 'low-carbon transition directly impacts China's dual carbon goals. Data reveals that national and provincial parks account for approximately 31% of the country's total carbon emissions, making them a critical sector for emission reduction. Against this backdrop, the transition of "zero-carbon parks" from concept to practice has emerged as a key driver for regional green and high-quality development [1].

However, current zero-carbon park planning suffers from two critical issues: "technological superficiality" and "path ambiguity." Many proposals merely stack low-carbon technologies like photovoltaics and energy storage without systematic top-level design or holistic optimization [2]. This results in low system integration, insufficient coordination, poor economic viability, and even operational safety risks. Therefore, there is an urgent need to establish a systematic planning framework that guides parks to transition from traditional energy consumers to integrated, intelligent, and low-carbon comprehensive energy producers.

The central question of this study is: How to construct a universal theoretical model for comprehensive energy planning in zero-carbon industrial parks? This model must systematically address key aspects including planning objectives, boundaries, critical components, optimization methods, and dynamic mechanisms. Starting with an analysis of theoretical connotations, this paper establishes a three-phase universal framework for planning pathways, elaborates core methodologies, and examines key challenges and countermeasures in planning and implementation, aiming to provide systematic theoretical references for both academia and practice [3,4].

2. Theoretical Connotation and System Characteristics of Zero-carbon Park Integrated Energy System

The zero-carbon park integrated energy system is not merely an upgrade to traditional energy supply models, but a systemic transformation encompassing technology, institutional frameworks, and management practices. The theoretical framework can be defined as follows: Within clearly delineated geographical and administrative boundaries, through systematic innovation, it establishes a regional energy ecosystem where high proportions of localized renewable energy form the core, organically integrating diverse energy forms including electricity, thermal energy, cold energy, and hydrogen [5]. By leveraging intelligent cyber-physical systems, it achieves high-level coordination and dynamic equilibrium among "source-grid-load-storage" components, ultimately realizing net-zero carbon emissions and carbon removal within the park's annual operational scope.

The system has the following core system features:

Multi-energy flow coupling and cascaded utilization: The system breaks away from the traditional model of separate planning and isolated operation of energy subsystems such as electricity, heat, and gas. It emphasizes the conversion and coupling of different energy forms through technologies like heat pumps, electricity-to-hydrogen, waste heat recovery, and combined cooling, heating and power (CCHP). For example, surplus photovoltaic power can be used for water electrolysis to produce hydrogen, while low-grade waste heat from industrial production can be utilized for district heating. This approach maximizes the utilization of energy grades, thereby significantly enhancing overall energy efficiency at the system level.

The interplay between generation, grid, load, and storage with flexible controllability: The volatility of renewable energy and the diversity of load demands require systems with robust flexible regulation capabilities. This necessitates the integration of energy storage devices (electrochemical storage, thermal storage, hydrogen storage), flexible loads (interruptible and adjustable loads), and smart microgrids to transform passive "loads" into controllable "resources". These elements enable real-time interaction with "power sources" and "networks", collectively ensuring the system's safety, stability, and economic efficiency.

Collaborative Carbon Flow Management and Dual-Flow Optimization: Unlike traditional energy planning that focuses solely on energy flows, zero-carbon park planning must simultaneously consider carbon flows. This requires embedding carbon emission intensity or total carbon emission indicators into the objective function and constraints of the planning model, shifting from single-objective optimization of energy costs to a paradigm of multi-objective collaborative optimization encompassing "economy, low-carbon performance, and reliability and carbon asset value realization." The generation, transfer, and consumption processes of energy flows and carbon flows within the system are tracked and optimized in real-time

3. General Framework for Planning Pathways of Integrated Energy System in Zero-Carbon Industrial Park

Based on the above system characteristics, this study proposes a general three-stage planning framework. The framework emphasizes systematic planning, foresight, and dynamic adaptability, with its core logic being the spiral progression of "cognitive system-design system-management system" [6].

3.1. Phase I: Baseline Diagnosis and Multi-scenario Construction

Accurate assessment of current conditions and forecasting of future scenarios form the foundation of scientific planning. The core objective of this phase is to complete a comprehensive "profile" of the park's energy and carbon metabolism [7].

Comprehensive Analysis of Energy and Carbon Flows: Establishing Energy Balance Sheets and Carbon Inventories for Industrial Parks. Conduct detailed accounting of all energy inputs, conversions, transmission, distribution, end-use consumption, and losses within the park over the past 3-5 years. Utilize internationally recognized methodologies (e.g., ISO 14064 standards or national corporate accounting guidelines) to convert energy consumption data into carbon emission data, identifying key emission sources and potential reduction opportunities [8].

Refined Evaluation of Resource Potential and Load Characteristics: This approach not only assesses the physical space potential of rooftops, vacant lots, and other areas suitable for deploying distributed photovoltaic and wind power systems, but also integrates local meteorological data to generate high spatiotemporal resolution renewable energy output time series curves. Simultaneously, it conducts detailed modeling of various loads including industrial, commercial, and public buildings, analyzing their daily/seasonal variation patterns, adjustable potential, and future growth trends [9].

Multi-scenario construction: Based on industrial development planning, technological progress expectations, and carbon constraint policy intensity (e.g., carbon tax price), construct multiple future development scenarios including baseline scenario, enhanced policy scenario, and technological breakthrough scenario to provide different boundary conditions for subsequent optimization planning (Table 1).

Table 1. Core Tasks and Outputs of the Three-Phase Planning Path.

planning stage	Core Input	Key Methods and Tools	Main output results
1. Baseline Diagnosis and Scenario Construction	Historical energy data, industrial planning, geographic information, policy documents	Energy audit, carbon accounting, resource GIS assessment, scenario analysis	Energy carbon flow map, resource potential report, multi-scenario description document
2. Multi-objective Collaborative Optimization Planning	Output of Phase 1, technical and economic parameters, optimization objective weights	Multi-objective optimization algorithm, energy system modeling software, technical and economic evaluation	Optimal Technology Configuration Scheme, System Operation Strategy and Life Cycle Cost-Benefit Analysis
3. Dynamic Iterative Implementation and Evaluation	Optimize the planning scheme, real-time operational data, and external policy market changes.	Digital Twin Technology, Rolling Planning Method, and Key Performance Indicator Monitoring	phased construction plan, dynamic adjustment plan, annual evaluation report

3.2. Phase Two: Multi-objective Collaborative Optimization Planning

This stage is the core of the planning path, aiming to solve the optimal system configuration and operation strategy under the given situation and constraints by mathematical modeling and optimization algorithm.

Development of a planning optimization model: The model typically adopts a dual-core objective of minimizing both total lifecycle costs (including investment, operational maintenance, fuel, and carbon trading costs) and carbon emissions, with constraints such as power balance, thermal balance, physical operational limits of equipment, and carbon emission caps. The decision variables encompass equipment selection, capacity (e.g., photovoltaic installed capacity, energy storage power and capacity, heat pump heating capacity), and operational strategies for typical days [10].

Application of multi-objective optimization algorithms: Given the inherent trade-off between economic efficiency and low-carbon objectives, advanced techniques such as Non-Dominant Sorting Genetic Algorithm (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) are employed to derive a set of "Pareto optimal solutions". Decision-makers may select the final implementation plan from this solution set based on their specific strategic priorities for the industrial park, whether prioritizing short-term economic returns or long-term low-carbon leadership.

Sensitivity Analysis and Robustness Testing: Perform sensitivity analysis on key technical parameters (e.g., photovoltaic investment cost reduction rate, energy storage cycle life, future electricity prices, carbon prices) to evaluate the performance of the planning scheme under various uncertainties. When necessary, robust optimization methods can be introduced to enhance the resilience of the planning scheme in addressing future risks.

3.3. Phase III: Dynamic Iterative Implementation and Evaluation

The planning scheme is not a static blueprint, but a dynamic "living document".

Develop a phased implementation roadmap: Break down the long-term optimization plan into specific construction task packages for the near-term, medium-term, and long-term, clearly defining the technical priorities, investment estimates, and expected emission reduction outcomes for each phase.

Establishing a Digital Twin Support Platform: Deploy the digital twin system concurrently with or prior to the physical system construction. This platform utilizes real-time operational data to create a mirrored simulation of the physical system, enabling the testing of new operational strategies, assessment of equipment failure impacts, and prediction of future energy supply and demand. It serves as a powerful tool for real-time optimization scheduling and long-term planning with iterative adjustments.

Establish a closed-loop monitoring-evaluation-optimization system: Develop a key performance indicator (KPI) framework covering energy self-sufficiency rate, carbon intensity reduction rate, system-wide energy efficiency, and peak-valley difference rate. Regularly compare actual operational data with planned expectations. When deviations exceed threshold values or significant changes occur in external conditions, trigger the re-evaluation and iterative optimization of the planning scheme.

4. Key Technology Integration and Methodology in Path Planning

The effectiveness of the planning path depends on the integration of a series of key technologies and methodologies.

4.1. Unified Modeling and Collaborative Optimization Method for Multi-energy Flow

A critical element in integrated energy system planning is the management of heterogeneous energy flows, including electricity, thermal energy, cooling, and hydrogen. This involves the establishment of unified energy bus models to represent complex interactions among generation, storage, and conversion devices such as gas turbines, heat pumps, electrolyzers, and battery storage systems. Energy conversion matrices describe the quantitative relationships between input and output flows across these devices, enabling accurate system-level analysis. On this basis, optimization methods such as mixed-integer linear programming (MILP), nonlinear programming, or hybrid metaheuristic algorithms can be employed to identify global optimal solutions under multiple operational and economic constraints. Collaborative optimization also integrates cross-device and cross-node interactions, balancing local and system-wide objectives to achieve maximal efficiency and minimal energy loss. Advanced sensitivity analysis and scenario simulation are used to ensure the solutions are robust against uncertainties in technology performance, market conditions, and demand fluctuations.

4.2. Resource-load Matching Analysis Considering Spatiotemporal Characteristics

High penetration of renewable energy requires careful temporal and spatial coordination between energy supply and demand. Hourly time-series simulations covering a full year (8,760 hours) are employed to evaluate the alignment between renewable energy generation profiles and load curves, determining the necessary energy storage capacity and optimal charging-discharging strategies. Spatial optimization leverages Geographic Information Systems (GIS) and energy network modeling to strategically deploy distributed energy resources, reduce transmission losses, and enhance system resilience. Planning models must also account for uncertainties such as fluctuations in solar irradiance, wind speed, and load growth, as well as evolving technological and market conditions.

Table 2 summarizes key parameter categories, specific examples, sources of uncertainty, and planned responses in the integrated energy system planning model. This table provides a structured framework for addressing technical, economic, market, and resource/load uncertainties, ensuring that the planning methodology is robust and adaptable.

Table 2. Key Parameters and Uncertainties to Be Prioritized in the Planning Model.

Parameter category	Example of specific parameters	uncertain source	Planned response
technical economic parameter	Unit investment cost, equipment efficiency, and lifespan of PV/energy storage systems	The speed of technological advancement and the expansion of market scale	Using learning curve to predict future costs and conduct multi-scenario sensitivity analysis
market policy parameter	Electricity price, carbon trading price and renewable energy subsidy	Policy adjustment and market fluctuations	Design robust solutions or introduce financial hedging tools
resource and load parameter	solar irradiance, wind speed, load growth rate	Climate Change and Uncertainty of Industrial Development	Using historical meteorological data to build statistical models for constructing elastic load prediction intervals

4.3. Application of Digital Twin Technology in Full Cycle Planning

Digital twin technology provides a comprehensive approach that spans the entire lifecycle of integrated energy system planning. In the design phase, digital twins enable multi-dimensional simulation of alternative planning schemes, allowing planners to conduct comparative analyses, evaluate technical feasibility, and assess system performance under various scenarios. This approach supports iterative refinement of design solutions, reduces the risk of design errors, and facilitates data-driven decision-making.

During the construction and implementation phase, digital twin models synchronize closely with physical systems, enabling real-time monitoring, coordinated deployment, and virtual testing of equipment and processes. By simulating construction sequences, energy conversion interactions, and operational contingencies, planners can anticipate potential issues, optimize workflows, and reduce delays or resource wastage.

In the operation and maintenance phase, digital twins provide continuous predictive analytics, virtual testing, and real-time optimization of energy flows. They can monitor system health, detect anomalies, forecast equipment maintenance needs, and suggest operational adjustments to improve efficiency and reliability. This creates a dynamic feedback loop where operational data continuously informs model updates, allowing the virtual system to evolve alongside the physical system.

Overall, digital twin technology establishes a virtual replica that accurately mirrors physical energy systems while enabling interactive simulation and iterative optimization. Its application enhances the scientific rigor of planning, improves operational precision, and supports robust decision-making under uncertainties, making it a key enabler for high-efficiency, sustainable, and resilient integrated energy systems.

5. Key Challenges and Theoretical Countermeasures in Planning and Implementation

Although the planning methodology is becoming more and more perfect, there are still many theoretical and mechanism challenges in practice.

5.1. Key Challenges

A new challenge in system stability and reliability: Distributed power sources with high-proportion inverter interfaces alter the system's inertia and short-circuit capacity characteristics, and the randomness and volatility of high-proportion renewable energy generation potentially cause voltage fluctuations and frequency stability issues. The traditional power system stability theory based on large-scale power sources requires re-evaluation and refinement for park-level microgrids.

Cross-departmental collaboration and institutional costs: The integrated energy system involves multiple regulatory bodies including energy, housing and urban-rural development, industry and information technology, and environmental protection. Its planning, construction, and operation require breaking through traditional administrative and sectoral barriers. Currently, institutional inconsistencies in project approval, grid connection standards, and pricing mechanisms constitute significant "institutional costs".

Economic risks of long-term investment: Zero-carbon systems typically require substantial initial investments, while long-term returns depend on future electricity prices, carbon prices, and equipment performance degradation rates, which introduce significant uncertainty. The key economic factor for the feasibility of such planning lies in designing business models and financing mechanisms that can effectively mitigate risks and attract diversified investments.

5.2. Theoretical Countermeasures

Deepening theoretical research on the coordinated stability of "source-grid-load-storage" system: The planning model should not only consider steady-state energy balance but also incorporate dynamic stability constraints such as frequency response and voltage support. This study explores technical approaches and configuration methods to leverage the rapid response capabilities of distributed energy storage and controllable loads, thereby providing virtual inertia and frequency regulation auxiliary services for the system.

Advancing an integrated "planning-policy-market" framework: While developing technical plans, concurrently formulate supporting policy recommendations-including green power trading rules for industrial parks, grid access fees for distributed generation's "wall-to-wall electricity sales," and differentiated pricing based on energy efficiency and carbon footprint. This approach elevates planning from a purely technical document to a comprehensive "technology-institution" solution.

Innovative evaluation and financing models based on full life cycle value: This initiative advances financial assessment frameworks beyond basic payback period calculations, incorporating environmental value (carbon reduction), social value (employment and technology demonstration), and systemic value (reduced grid investment and enhanced power supply reliability). It also explores asset securitization financing models grounded in future stable cash flows, such as energy-saving benefits and carbon asset returns.

6. Conclusion

The planning of a zero-carbon park's integrated energy system is a complex systems engineering endeavor. Its success lies not in mechanically listing technical specifications, but in scientifically designed and dynamically managed approaches grounded in profound systemic understanding. The three-phase framework of "baseline diagnosis-optimized planning-iterative implementation" proposed in this paper, along with its core principles-multi-objective synergy, multi-energy flow coupling, carbon-energy flow synchronization, and digital twin empowerment-aims to provide a methodologically significant planning tool that transcends specific case studies.

Looking ahead, the planning and research of zero-carbon parks need to be continuously deepened in the following directions: First, develop more efficient and precise large-scale, multi-time-scale coupled optimization algorithms to handle more complex system forms; Second, establish a more comprehensive methodology for park-level carbon measurement, monitoring, and verification to provide a foundation for precise carbon control; Third, strengthen interdisciplinary integration research between energy system planning and urban planning, industrial planning, to truly achieve coordinated optimization of spatial layout, industrial development, and energy structure. Only through continuous theoretical innovation and methodological improvement can we steadily and efficiently promote the transition of China's zero-carbon parks from blueprint to reality, contributing China's wisdom and solutions to the low-carbon transformation of global cities and industrial zones.

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