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ОБЗОР СУЩЕСТВУЮЩИХ ПОДХОДОВ К ВЫБОРУ МЕСТ РАЗМЕЩЕНИЯ ЗАРЯДНЫХ СТАНЦИЙ И СТАНЦИЙ ЗАМЕНЫ БАТАРЕЙ ЭЛЕКТРОМОБИЛЕЙ

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A Review of Existing Approaches to Site Planning of Electric Vehicle Charging and Swapping Stations

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1. Introduction

With the worsening global climate change, reducing carbon emissions and transforming the energy structure have become a global consensus. As a major source of carbon emissions, the transportation sector relies on promoting electric vehicles to achieve the "carbon peaking and carbon neutrality" goals [1]. As an indispensable supporting infrastructure, charging and swapping stations undertake core energy supply and travel guarantee functions. Their rational site planning is directly related to the convenience of electric vehicle use, user experience, operational efficiency, investment return and optimal allocation of energy resources.

Therefore, researching charging and swapping station site planning to solve current pain points is of great theoretical and practical significance for improving the charging infrastructure system, promoting the sustainable development of the electric transportation industry, and helping achieve the "dual carbon" goals. This paper conducts a systematic study on site planning, sorting out development status, summarizing research results, analyzing existing problems, and proposing future research directions.

2. Development Status of the Global and Chinese Electric Transportation Markets

2.1 Development Status of the Global Electric Transportation Market

Driven by global policy support, technological progress and improved environmental awareness, the electric transportation market has grown rapidly, with electric vehicles becoming the core direction of global automotive industry transformation. In 2025, global electric vehicle sales exceeded 20 million units, a significant increase from 17 million in 2024, accounting for 26% of the global new car market. Coupled with the 13% market share of hybrid electric vehicles, nearly 40% of new cars are electrified, and most new cars are expected to be electrified by 2035.

The global scale of charging and swapping stations continues to expand, but regional layout is unbalanced: Europe and China focus on comprehensive charging network coverage, while North America relies more on private charging facilities [2]. Charging and swapping technologies are upgrading, with high-power charging and battery swapping modes widely promoted, but inconsistent standards across regions restrict cross-regional service interconnection [3].

2.2 Development Status of the Chinese Electric Transportation Market

As a global leader in the electric transportation industry, China leads in policy support, technological innovation and market scale. In 2025, China's automobile production and sales reached 34.531 million and 34.4 million units respectively (17 consecutive years as the world's first), and new energy vehicle production and sales hit 16.626 million and 16.49 million units (11 consecutive years as the world's first), accounting for 47.9% of new car sales [4].

China has built the world's largest and most diverse charging infrastructure system [5], with over 20 million charging facilities by the end of December 2025. It is accelerating the construction of a "urban planar, highway linear, rural point-like" charging network. However, obvious shortcomings exist: insufficient charging pile density in urban core areas, weak coverage in suburban and rural areas, concentrated swapping stations in a few cities, and poor connection between some stations and the power grid, all closely related to unreasonable site planning [6].

2.3 Importance of Charging and Swapping Station Planning

The importance of charging and swapping station planning is reflected in three aspects: first, it supports the high-quality development of the electric vehicle industry by solving users' "range and charging anxiety" and driving the coordinated development of related industries; second, it optimizes the energy structure and helps achieve "dual carbon" goals by promoting renewable energy consumption and improving energy utilization efficiency[7]; third, it improves the urban transportation system and governance level by integrating with urban infrastructure and alleviating traffic congestion.

3. Literature Review on Site Planning of Electric Vehicle Charging and Swapping Stations

3.1 Mainstream Methods of Current Site Planning

Current mainstream methods for electric vehicle charging and battery swapping station site planning can be divided into three categories: mathematical programming methods, heuristic/metaheuristic algorithms, and simulation-based optimization methods. Each category has distinct characteristics in terms of solution accuracy, computational efficiency, and applicable scenarios.

1.Mathematical Programming Methods

Linear Programming (LP), Nonlinear Programming (NLP), and Mixed Integer Linear Programming (MILP) are classical location optimization tools. LP is suitable for scenarios where both the objective function and constraints are linear, offering fast solution speeds but limited flexibility. NLP can handle nonlinear relationships, such as the coupling between charging time and battery state, but at higher computational complexity. MILP addresses discrete "whether to build" decisions through 0-1 decision variables, making it appropriate for large-scale urban network planning. In recent years, stochastic programming has been introduced to cope with demand uncertainty and dynamic changes in electric vehicle penetration rates, enhancing the adaptability of solutions to future urban development. However, mathematical programming methods face the "curse of dimensionality" when solving NP-hard problems, making it difficult to handle multi-objective trade-offs and complex user behavior modeling.

2. Metaheuristic Algorithms

Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) are currently the most widely applied intelligent optimization algorithms [8]. GA achieves global search through crossover and mutation operations, excelling at multi-objective problems but suffering from slow convergence and susceptibility to local optima. PSO leverages swarm intelligence for rapid convergence, suitable for dynamic environments, but experiences declining population diversity in later stages leading to premature convergence. To address these limitations, scholars have proposed various improvement strategies: for instance, Chaotic Catfish Particle Swarm Optimization (CPSO) enhances the ability to escape local optima by perturbing stagnant populations through the "catfish effect"; multi-objective evolutionary algorithms such as NSGA-III, combined with TOPSIS decision-making methods, can achieve Pareto optimality among construction costs, user satisfaction, and charging convenience. Hybrid algorithms (such as GA-PSO) combine the advantages of different algorithms, performing better when handling high-dimensional, multi-constraint problems [9].

3. Simulation-Based Optimization Methods

Considering the high uncertainty of electric vehicle charging behavior, Agent-Based Modeling (ABM) and discrete event simulation have become important supplements. Monte Carlo simulation can quantify grid load fluctuations and user queuing waiting times under different charging scenarios; embedding queuing theory (such as M/M/s/K models) into location models enables the evaluation of service capacity and congestion levels' impact on user choices. These methods can capture complex interactions in real traffic networks but at high computational costs, and are typically used in combination with heuristic algorithms [10].

The following is a comparative analysis of three methods (Table 1).

Table 1 – Comparative Analysis of Electric Vehicle Charging and Swapping Stations Site Planning Methods

Method Category	Specific Method	Core Principle	Main Advantages	Main Limitations	Typical Application Scenarios
Classical Mathematical Programming	Linear Programming (LP)	Linear objective function and constraints	Fast solving speed, theoretically complete, global optimality guarantee	Only applicable to linear relationships, limited flexibility	Small-scale deterministic site selection, cost minimization
	Nonlinear Programming (NLP)	Handles nonlinear objective functions and constraints	Can characterize coupling between charging time and battery state	High computational complexity, convergence difficulties	Dynamic charging power optimization, battery health modeling
	Mixed Integer Linear Programming (MILP)	Introduces 0-1 variables for discrete location decisions	Can simultaneously optimize site selection and capacity configuration	Difficult to solve when variables increase, "curse of dimensionality"	Large-scale urban charging network planning
	Stochastic Programming	Introduces random variables to describe demand uncertainty	Adapts to dynamic changes in EV penetration rates	Large computational burden for scenario generation	Long-term strategic planning, uncertain environments
Metaheuristic Algorithms	Genetic Algorithm (GA)	Simulates natural selection, crossover and mutation evolution	Excellent at multi-objective optimization, strong global search capability	Slow convergence, prone to local optima	Multi-objective trade-offs, complex constraint conditions

Method Category	Specific Method	Core Principle	Main Advantages	Main Limitations	Typical Application Scenarios
	Particle Swarm Optimization (PSO)	Simulates bird flock foraging, swarm intelligence optimization	Fast convergence speed, suitable for dynamic environments	Declining population diversity in later stages, premature convergence	Real-time scheduling, dynamic demand response
	Improved Algorithms (CPSO/NSGA-III)	Introduces chaotic perturbation/nondominated sorting	Escapes local optima, achieves Pareto frontier	Complex parameter tuning	High-dimensional multi-objective optimization problems
	Hybrid Algorithms (GA-PSO)	Combines advantages of multiple algorithms	Balances global exploration and local exploitation	Complex algorithm structure, difficult implementation	NP-hard combinatorial optimization problems
Simulation Optimization Methods	Monte Carlo Simulation	Random sampling to estimate system behavior	Quantifies uncertainty impact, risk analysis	High computational cost, results dependent on distribution assumptions	Charging demand forecasting, grid load assessment
	Agent-Based Modeling (ABM)	Simulates individual interactions to emerge macroscopic behavior	Captures user behavior heterogeneity and social effects	Difficult model calibration, computationally intensive	User behavior analysis, market evolution simulation
	Queuing Theory Models (M/M/s/K)	Analyzes service system congestion and waiting	Evaluates service capacity and user satisfaction	Strict assumptions, limited real-world applicability	Charging pile quantity configuration within stations, service level optimization

From the perspective of solution efficiency, mathematical programming methods provide theoretical guarantees for small-scale deterministic problems, while metaheuristic algorithms are more suitable for large-scale, multi-objective complex scenarios; from a practical standpoint, Voronoi diagram-based spatial partitioning methods can dynamically delineate service areas, resolving the overlap ambiguity of traditional circular coverage models. Current research trends exhibit three characteristics [11]: first, multi-objective optimization has become mainstream, simultaneously balancing investor costs, user experience, and grid security; second, data-driven methods are emerging, utilizing trajectory big data to identify real charging demand hotspots; third, bi-level programming models are gaining attention, with the upper level optimizing site layout and the lower level simulating user equilibrium choice behavior, more closely reflecting market competition realities. In the future, integrating artificial intelligence prediction models with robust optimization frameworks to enhance the resilience of planning solutions under uncertain conditions such as equipment failures and grid disturbances will be an important development direction in this field [12].

3.2 Shortcomings of Current Planning Methods

Despite the rich methods, there are four main shortcomings in practical application:

1. Insufficient multi-factor coordination: Most studies focus on single or few factors, ignoring the collaborative impact of power grid capacity, land resources, fire safety, etc., leading to unfeasible operation after station completion [13].
2. Lack of dynamic adaptability: Static data-based planning fails to adapt to the rapidly changing electric vehicle market, including user demand, technology and policies [14].
3. Insufficient data support: Imperfect data sharing mechanism leads to data missing, inconsistency and delay, restricting planning accuracy [15].
4. Lack of full-life-cycle perspective: Overemphasis on the construction stage ignores operational benefits, resulting in difficulty in profitability and sustainable operation of some stations [16].

4. Research Needs and Future Research Directions

4.1 Summary of Current Research Needs

The core research needs are concentrated in three aspects: first, planning methods for multi-scenarios (residential communities, highways, rural areas) and multi-modes (charging, swapping), especially swapping station layout methods; second, dynamic coordinated planning and emergency response to adapt to market changes and meet emergency charging needs; third, data sharing and intelligent planning to improve planning accuracy and efficiency.

4.2 Outlook on Future Research Directions

Combined with research needs and industry trends, future research directions are as follows:

1. Special planning for multi-scenarios and multi-modes: Study scenario-specific planning methods and focus on swapping station layout to promote coordinated charging and swapping development.
2. Dynamic coordinated planning and emergency response: Construct a dynamic coordination model with electric vehicle development, power grid and urban planning,

and establish a demand forecasting update mechanism and cross-regional coordination methods.

3. Intelligent planning technology and data sharing: Establish an industry data sharing mechanism and unified platform, optimize models with intelligent technologies, and promote the unification and internationalization of charging standards.

4. Interdisciplinary integration: Integrate with transportation engineering, urban planning, economics, etc., and strengthen international cooperation to improve China's charging and swapping station planning level.

References:

[1] Xia Y C, Han G T. Exploration and Practice of Electric Vehicle Charging Facility Planning Under the Background of "Dual Carbon"[J]. Comprehensive Transportation, 2024, 46(12): 20-25.

[2] Vyacheslav Voronin, Fedor Nepsha, Pavel Ilyushin. Determining Volt/Var Characteristics of Electric Vehicle Charging Station Inverters for Voltage Regulation in Distribution Networks[J]. World Electric Vehicle Journal, 2024, 15(553).

[3] B Y Z A, A Z S, B Y Z, et al. A Systematic Methodology for Mid-and-Long Term Electric Vehicle Charging Load Forecasting: The Case Study of Shenzhen, China[J]. Sustainable Cities and Society, 56 [2025-01-03].

[4] Yu Z L. Research on Layout Planning Methods of Urban Electric Vehicle Charging Facilities[D]. Xi'an: Chang'an University, 2023.

[5] Meng X, Zhang W, Bao Y, et al. Sequential Construction Planning of Electric Taxi Charging Stations Considering the Development of Charging Demand[J]. Journal of Cleaner Production, 2020, 259: 120794.

[6] Ma X. Research on Site Selection Planning of Electric Vehicle Charging Stations[Master's Thesis]. Inner Mongolia: Inner Mongolia University, 2025.

[7] Wei J L. Research on Electric Vehicle Charging Demand Forecasting and Planning Layout[J]. Comprehensive Transportation, 2025, 47(12): 20-25.

[8] Shen L Z, Wang D F. Site Selection Planning of Electric Vehicle Charging Stations Based on Improved Genetic Algorithm[J]. Transportation Energy Conservation and Environmental Protection, 2025, 21(111): 32-36.

[9] Zhou X Y. Research on Construction Planning of Electric Vehicle Charging and Swapping Stations Based on Multi-Objective Optimization[Master's Thesis]. Beijing: North China Electric Power University, 2024.

[10] Duo J N, Zhang M K, Yao Y, et al. Planning and Management of Electric Vehicle Charging Stations from the Perspective of Sustainable Development[J]. Automobile and New Power, 2023, 6(06): 16-19.

[11] Cao J J, Wang C, Huo C H, et al. Optimal Planning of Charging Stations Considering Distribution Network Load Fluctuation and Voltage Deviation[J]. Journal of Electric Power Science and Technology, 2021, 36(04): 12-19.

[12] Wang Z P, Zhang J, Liu P, et al. A Review of Research on Electric Vehicle Charging Station Planning[J]. China Journal of Highway and Transport, 2022, 35(12): 230-252.

[13] Zhang Z Y, Wang Z J, Yang W H, et al. Research on Site Selection Planning of Electric Vehicle Charging Stations Based on Charging Demand Forecasting[J]. Electrical Measurement and Instrumentation, 2024, 61(10): 39-49.

[14] Wang H P, Gao R. Layout Optimization of Electric Vehicle Fast and Slow Charging Stations Based on Improved Particle Swarm Optimization[J]. Systems Engineering, 2023, 41(04): 95-103.

[15] Gao M H. Research on Charging Pile Location Planning Method Based on Multi-Objective Fusion[D]. North China Electric Power University (Beijing), 2020.

[16] Wang Y Q, Wang X, Cong R C, et al. Charging Guidance Strategy for Traveling Electric Vehicles Considering Distribution Network Operation Safety[J]. High Voltage Engineering, 2023, 49(05): 2131-2139.