

A Review on the Current Status and Development Trends of Electric Vehicle Charging Infrastructure in China

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Abstract: As the global energy system accelerates its transition toward decarbonization, China's new energy vehicle (NEV) industry has demonstrated robust growth momentum. With production and sales surpassing 9 million units and a market penetration rate exceeding 30% in 2023, the industry has emerged as the core engine for implementing the carbon neutrality strategy within the transportation sector. However, a significant spatio-temporal mismatch exists between the construction of charging infrastructure and industrial expansion. Structural contradictions such as unbalanced vehicle-to-charger ratio, uneven spatial distribution, single profit mechanism and weak safety protection system have become a critical bottleneck restricting the scaled development of the industry, underscoring the practical necessity of this research. Adopting a full-industry-chain perspective, this study systematically reviews and synthesizes existing research on current pain points, planning evolution, and cutting-edge technological innovations in this field. In-depth discussions are conducted centering on key research dimensions including demand forecasting, layout optimization, distribution network coordination and subsidy effect maximization. This review reveals that existing studies collectively confirm that the application of multi-objective programming models, the "vehicle-charger-road-grid" integration drive, and Vehicle-to-Grid (V2G) technology can effectively promote the synergistic enhancement of facility operational efficiency and power grid adaptability. These synthesized conclusions provide significant theoretical and practical support for breaking through the developmental bottlenecks of charging infrastructure and facilitating the high-quality advancement of the NEV industry.

Keywords: Electric Vehicle; Charging Infrastructure; Charging Station Planning; Distribution Network Hosting Capacity; Vehicle-to-Grid (V2G) Technology

1. Introduction

Under the macro-architecture of the in-depth advancement of the national "dual carbon" strategy and the reconstruction of the energy and power system, China's new energy vehicle (NEV) industry has crossed the critical point of the market introduction phase, entering a entirely new development trajectory of exponential leap. According to the latest industry statistics, the production and sales volume of NEVs in China surpassed the 9-million-unit mark in 2023, with a market penetration rate exceeding 30% [14]. This data not only signifies the explosive expansion of industrial scale but also establishes its status as the core engine for implementing the carbon neutrality strategy within the transportation sector, with its development rate continuing to lead the global transition process. As the key physical infrastructure supporting this massive closed-loop industrial ecosystem, the scientific planning, spatial accessibility, and operational efficiency of the charging facility network directly constitute the determinant variables for the promotion depth of the green transportation paradigm. However, examining the existing academic landscape, although related research outputs have grown geometrically, significant cognitive limitations and methodological lags still exist in the multi-dimensional systemic analysis coping with industrial structural changes, and an efficient closed-loop feedback mechanism has not yet been formed between theoretical research and engineering practice[3].

A critical review of the existing literature reveals that mainstream research paradigms still fall short when dealing with complex system coupling issues. A systematic retrospective

analysis of the charging station planning domain by Wang Zhenpo et al. [7] reveals that current research is mostly confined to the static optimization of a single objective function or linear extrapolation based on historical data. In terms of dynamic adaptability to the complex giant system of "vehicle-charger-road-grid" and responsiveness to rapid technological iteration, it exhibits obvious time-lag characteristics, making it difficult to capture the randomness of user travel behavior and the non-linear laws of spatio-temporal distribution. At the level of economic incentive mechanisms, although Yue Weizhong et al. [15], based on a game theory perspective, empirically demonstrated the positive driving mechanism of government subsidy efficacy on operators' construction scale-confirming the critical role of policy tools during the market cultivation period-their research scope has not yet fully extended to penetration strategies in non-core regional markets (such as lower-tier markets and rural areas). Furthermore, the lack of in-depth discussion on dynamic planning synergy mechanisms limits the explanatory power of theoretical models in scenarios of unbalanced regional development. Concurrently, while methodological innovations have seen breakthroughs, boundaries remain. Although the comprehensive planning model proposed by Tian Mengyao et al. [13] innovatively introduced Markov chains and the entropy weight method to enhance the scientificity and objectivity of decision weights, the model's system robustness and generalization capability still lack sufficient empirical validation when facing high-dimensional scenarios such as extreme meteorological environmental disturbances, multi-station collaborative operation, and complex constraints on the grid side.

Given the aforementioned dual gaps at both theoretical and practical levels, this study is dedicated to deeply deconstructing the heterogeneous characteristics of EV charging facilities in regional distribution, the bottleneck of homogenized profit models, and the current status of safety protection systems from a systematic perspective of the entire industry chain, thereby clarifying the underlying trends and structural contradictions of industrial development. On this basis, this paper further evaluates the policy dividends and technological window periods released by the energy transition,

dialectically analyzes the market cognitive biases and service homogenization dilemmas existing in the industry's evolutionary process, and integrates cutting-edge technological pathways with policy toolkits. This aims to construct a co-evolutionary framework encompassing the physical infrastructure, the automotive industry, the power grid system, and the policy system, exploring the equilibrium of interests among multiple stakeholders. The theoretical contribution of this study lies in attempting to fill the theoretical vacuum in dynamic demand adaptation and multi-agent collaborative mechanisms through cross-disciplinary integration[3]. Its practical value is reflected in providing statistically significant quantitative bases and strategic guidance for the precise optimization of government subsidy policies, scientific decision-making in corporate technological pathways, and the continuous evolution of the industrial ecosystem.

2. Current Development Status of Electric Vehicle Charging Facilities

2.1 Scale Expansion and Technological Empowerment

Relying on the smooth transition of the new energy vehicle (NEV) industry from a policy-dividend-driven phase to a market-mechanism-dominated phase, the charging infrastructure sector has established significant large-scale agglomeration advantages and industrial synergistic effects. To date, China has successfully built an energy replenishment network system with the deepest coverage and the largest geographical span globally. Its service reach not only extends deep into 404 cities nationwide but also preliminarily outlines, in the spatial dimension, a high-power fast-charging backbone axis for expressways with the "Ten Vertical, Ten Horizontal, and Two Rings" network as its core framework [14,15]. While the density of the physical network continues to climb, the technological application level is shifting from the initial single-functional gap-filling construction to an innovative evolutionary paradigm characterized by high dimensionality and intellectualization.

Specifically, demand forecasting models based on multi-source heterogeneous data fusion of "vehicle-charger-road-grid", bidirectional energy interaction technologies such as Vehicle-to-Grid

(V2G), and multi-objective evolutionary optimization models are currently in a critical transition period from laboratory environment validation to large-scale engineering implementation. By introducing the IEEE 33-bus distribution system for simulation verification, Tian Mengyao et al. [13] confirmed the universal value and robustness boundaries of their planning model under complex distribution network topological constraints from the underlying logic. This research outcome significantly strengthens the scientific adaptation weight between facility layout planning and the hosting capacity of urban distribution networks. Driven by the dual spiral of technological progress and scale effects, the policy support system has also undergone a profound logical reconstruction, with its core orientation strategically migrating from "direct subsidies at the purchasing end" to "comprehensive incentives at the operational end." By integrating a diversified portfolio of policy tools encompassing investment scale, power density, operational efficiency, and service quality scoring, the underlying endogenous power for industrial growth is profoundly shifting from administrative directive-driven to an endogenous growth path dominated by market efficiency and service quality [12].

2.2 Structural Shortcomings and Restricting Factors

Although the overall scale of infrastructure exhibits an exponential growth trend, the structural contradictions and the risks of imbalanced factor allocation latent deep within the industry remain severe. In the geographical dimension of spatial allocation, facility layout demonstrates significant polarization effects and spatio-temporal asymmetrical characteristics. A resource mismatch pattern characterized by the coexistence of "oversaturated facility density in central urban areas" and "blind spots for energy replenishment in peripheral zones" has emerged in some core city clusters. This non-linear distribution of supply-demand imbalance not only significantly exacerbates the "charging anxiety" of end-users but also reveals the diminishing marginal effect of resource allocation efficiency in urban public spaces [8,11]. Wang Zhonghui et al.[5] conducted a systematic review of charging facility layout research and found that the unreasonable spatial distribution of facilities is a common problem in

most regions, which is closely related to the lack of in-depth investigation of regional demand differences in the planning stage. The research by Tian Mengyao et al. [13] further analyzes the underlying mechanism of this phenomenon: a severe correlation failure exists between the variance in regional land function positioning and the temporal characteristics of users' charging behaviors, leading to tremendous discreteness and uncertainty in facility utilization rates across spatio-temporal dimensions.

Shifting to the dimension of economic evaluation, the charging operation industry is facing the predicament of severely narrowed profit channels. Its commercial closed loop is highly constrained by the narrow-margin logic of electricity price differentials and single service fee revenues. Coupled with the lagging costs of high-frequency equipment maintenance cycles and the compatibility technical barriers of underlying protocols among various brands, most small and medium-sized operators bear immense liquidity pressure and financial default risks [1]. Meanwhile, the iteration rate of the safety prevention and control system has not yet been able to fully cover the risk demands of the battery's entire life cycle. Obvious technological vacuums still exist in diversified full-scenario applications for aspects such as multi-physics field early-warning mechanisms for battery thermal runaway and active isolation protection technologies under multi-fault coupling [4]. Furthermore, the high vehicle-to-charger ratio of 3.4:1 not only intuitively reflects the quantitative gap between the growth rate of energy replenishment facilities and the increase in vehicle ownership but also highlights the cognitive bias between the actual physical accessibility of facilities and the service satisfaction rate at the user end. This has become a common pain point that must be overcome in the current process of improving industrial quality and efficiency [11].

3. Opportunities and Challenges in the Development of Charging Facilities

3.1 Dividend Release and Innovation Momentum

The exponential leap in the production and sales volume of new energy vehicles (NEVs) has constructed a highly elastic growth space and scale dividend for the charging facility market. Meanwhile, the top-level drive of the "New

Infrastructure" strategy has deeply optimized the factor allocation and institutional environment of the industrial ecosystem. With the precise evolution of regulatory logic, the subsidy model has achieved a paradigm shift from a single purchase-end orientation to a composite incentive mechanism for "construction and operation." At the micro level, this evolutionary path, by reinforcing the hard constraints on the utilization rate of facility assets, has effectively curbed resource idleness and rent-seeking behaviors induced by early blind expansion, significantly enhancing the marginal efficiency of capital input and the sustainable endogenous power of the industry [15].

In the dimension of technological empowerment, the deep penetration of the Internet of Vehicles (IoV) architecture and machine learning algorithms reveals the inevitable trend of charging demand forecasting evolving from empirical extrapolation to high-precision, multi-dimensional spatio-temporal coupling logic. Concurrently, the accelerated implementation of the flexible microgrid model centered on "solar-storage-charging integration" provides critical technical support and physical barriers for alleviating the pressure of facility capacity expansion and achieving load balancing on the distribution network side [7,10]. Li Xiaomin et al.[3] pointed out that the popularization of charging infrastructure has a significant positive impact on the promotion of new energy vehicles, and technological innovation is an important bridge connecting the two. The concentrated release of such technological dividends is driving the profound leap of the industrial ecosystem from simple hardware stacking to a smart and networked stage characterized by the high coupling of energy flows and information flows.

3.2 Practical Constraints and Potential Risks

Despite the strong industrial momentum, the hard constraints posed by technical bottlenecks and operational risks still constitute deep-level challenges to the industry's development. At the forefront of technological research and development, the inherent conflict between the pulse-like demand for extreme fast-charging rates and the chemical stability as well as the cycle life degradation of power batteries remains a core contradiction urgently needing resolution in the current fields of electrochemical energy storage and power electronics. This physical

performance incompatibility not only limits the linear improvement of energy replenishment efficiency but also further exacerbates the asset impairment pressure on existing old facilities when facing high-power technological iterations [9].

At the operational practice level, the randomness and uncoordinated charging behaviors triggered by the large-scale integration of electric vehicles present severe tests for the hosting limits and dynamic regulation resilience of urban distribution networks. Empirical data from the research by Tian Mengyao et al. [13] reveals that high-density centralized grid-connection conditions can easily induce systemic risks such as distribution line overload, voltage deviation, and a surge in network losses. Furthermore, under the environment of hierarchical trading in the electricity market, the commercial logic framework of electric vehicle aggregators and the multi-party data security interaction protocols are still in the initial exploration stage, and a mature and robust value distribution mechanism has not yet been formed. In addition, the lack of coverage in non-core regional markets and the low management efficiency in long-tail markets largely dissipate the precise implementation effect of policy dividends. Wang Zhonghui et al.[5] also emphasized in their review that the uneven development of charging facilities between urban and rural areas is becoming increasingly prominent, and the layout in rural areas is seriously lagging behind, which restricts the comprehensive popularization of new energy vehicles. This leads the facility maintenance in lower-tier markets into a path-dependent inefficient predicament, severely restricting the process of the industrial ecosystem advancing towards region-wide equalization and service parity [8].

4. Collaborative Development Pathways and Optimization Strategies

4.1 Technical Dimension: Reconstruction of Multi-dimensional Optimization Systems

The underlying driving logic of industrial upgrading should focus on deepening the data-driven prediction system highly coupled with "vehicle-charger-road-grid" . By deeply drawing upon the academic framework proposed by Tian Mengyao et al. [13], the research perspective should be further broadened from a single physical constraint of the power grid to

the interactive influence of multi-dimensional variables, such as the heterogeneity of user travel behaviors, the seasonal fluctuations of power loads, and extremely complex meteorological factors. At the decision-making level of facility planning, there is an urgent need to strengthen the weight allocation mechanism for multi-objective optimization. Fully based on the differentiated spatio-temporal behavioral characteristics of short-term, high-frequency parking in commercial core areas and long-term, low-frequency parking in residential living areas, the dynamic proportional configuration and capacity margin optimization of fast/slow charging facilities must be precisely implemented to maximize the allocation efficiency of urban public resources [2].

Addressing the existing blind spots in charging safety perception and technological vacuums, constructing a high-reliability intelligent diagnostic model based on multi-fault physical field coupling mechanisms has become an urgent priority. Its core lies in improving and advancing industry-level safety testing specifications and risk defense systems through comprehensive monitoring data flows covering the entire life cycle of batteries [4]. Furthermore, relying on the sensitivity design of price-based demand response mechanisms and the flexible guidance strategies of coordinated charging, the flexible regulation potential of electric vehicles as mobile energy storage units can be deeply tapped. This deep-level interactive logic will drive the wide-area penetration of Vehicle-to-Grid (V2G) technology on the distribution network side. This not only effectively empowers the power grid's peak-shaving, valley-filling, and frequency regulation efficiencies but also fundamentally promotes the paradigm evolution of the energy replenishment system from traditional "passive integration" to smart "active support" [6,10].

4.2 Policy and Operation Dimension: Improvement of the Ecological Guarantee Mechanism

The precise delivery of policy tools and institutional supply should adhere to a significant differentiation-oriented principle. Addressing the endogenous lag in infrastructure construction in small and medium-sized cities and remote counties, efforts should be made to explore the implementation of gradient operational subsidies and public risk bottom-line

guarantee mechanisms based on the dimension of spatial equilibrium. At the level of top-level institutional linkage design, establishing an effective coupling mechanism between the "dual-credit" policy evaluation system and subsidies for charging infrastructure construction is conducive to overcoming long-standing administrative barriers, property rights and responsibilities conflicts, and obstacles in distribution capacity expansion, such as "charging piles entering residential communities," from the front end of the benefit distribution chain [12].

Concurrently, the operation end should be dedicated to completely breaking through the dual dilemma of singular profit logic and homogenized business models, actively exploring cross-boundary innovative business paradigms such as vehicle-charger resource sharing, dynamic wireless charging, and "energy + retail". By vertically integrating the upstream clean energy supply chain and horizontally extending the downstream digital information service chain, a composite industrial ecological chain with more diversified value dimensions can be constructed [1]. The systematic remodeling of this business ecology also needs to rely on unified digital information collaborative management platforms at the national and local levels to eliminate data silos. While finely reducing conflicts over the occupation of public resources, it guides user groups to establish a rational cognitive understanding of energy replenishment based on the laws of scientific energy utilization. Through the dual spiral drive of technological empowerment and institutional guarantees, the sustainable endogenous power of the industrial ecosystem will ultimately be significantly enhanced, promoting its deep coupling and synergistic evolution with the green transportation transition [7,8].

5. Conclusion

Deeply focusing on the field of electric vehicle charging infrastructure, this study systematically reviews the current status of industrial development, discriminates potential opportunities and practical challenges, and constructs a collaborative development pathway from multi-dimensional perspectives such as technological evolution, policy guidance, and business model optimization. It aims to provide solid theoretical support and practical guidance

for the high-quality leap of the industry and its deep coupling with the new energy vehicle industry.

This review indicates that China's EV charging facility industry has established significant large-scale agglomeration advantages, building the world's most extensive physical charging network. The dual-wheel drive of technological iteration and policy dividends constitutes the core logic of industrial evolution. Data-driven demand forecasting models integrating "vehicle-charger-road-grid", multi-objective evolutionary planning paradigms, and Vehicle-to-Grid (V2G) energy interaction technologies have opened up effective pathways for the intelligent upgrading of the industry. In particular, the planning model proposed by Tian Mengyao et al. [13], which comprehensively considers spatio-temporal charging demand and the hosting limit of the distribution network, has further broadened and enriched the scientific evaluation system of facility planning from the underlying methodological level [7,13].

However, the deep-seated structural contradictions concealed beneath scale expansion remain prominent. The surveyed literature shows that issues such as polarized regional layout distribution, the narrow-margin profitability of business models, systemic shortcomings in safety protection systems, and statistical imbalance in the vehicle-to-charger ratio are widespread. Technical R&D bottlenecks, operational marginal benefit constraints, the long-tail effect of regional development, and user-end cognitive biases all restrict the industry's quality improvement and efficiency enhancement to varying degrees [1,8]. Against the macro background where opportunities and risks coexist, the exponential growth potential of the NEV market, the dynamic upgrading of the policy system, and cross-innovation across multiple technological pathways continue to inject transitional momentum into the industry. This review confirms that relying on the precise evolution of the technical dimension and the ecological improvement of the policy and operational dimensions can effectively address the current pain points of the industry, driving the synergistic evolution of charging facilities, the automotive industry, and the power system. The empirical analysis based on a tripartite game perspective by Yue Weizhong et al. [15] also verifies that scientific institutional design and

flexible regulatory mechanisms are key variables for stimulating the vitality of market micro-entities and achieving industrial value balance [10,15].

Although this study strives for comprehensiveness, limitations requiring refinement still exist in multiple dimensions. Specifically, since the research samples and typical cases involved in the reviewed literature are mostly confined to first-tier cities and mature urban scenarios, insufficient attention has been paid to facility distribution patterns and differentiated energy supplement demands in non-core regional markets, especially small and medium-sized cities and vast rural areas, leading to limited wide-area applicability of the relevant research conclusions. Concurrently, discussions in existing studies on adaptability to complex dynamic scenarios-such as extreme weather disturbances, multi-station collaborative dispatching, and shortened technology iteration cycles-remain superficial, and the resilience boundaries and robustness of related planning strategies under extreme operating conditions still require further empirical verification. Furthermore, existing analyses of the dynamic coupling mechanisms between policy tools and technological innovations focus heavily on constructing static theoretical frameworks, lacking continuous tracking research on market regulation effects and long-term evolutionary pathways after the gradual phase-out of subsidy policies. Finally, regarding cognitive biases and cultural stereotypes among user groups, current discussions in the literature mostly focus on qualitative descriptions, and due to the lack of support from large-scale quantitative empirical data, there is still room for improvement in the targeted design of intervention strategies.

Standing at a new starting point of industrial evolution, future research can be further expanded along the following directions. The primary task is to broaden the geographical research scope, strengthening empirical investigations into facility layout planning, policy adaptability, and innovative business models in lower-tier markets and rural areas to fill the academic gap of current research in non-core regions. Furthermore, research on technology and policy adaptability under complex scenarios should be deepened, focusing on the impact of endogenous variables-such as extreme weather disturbances, multi-station dynamic synergy, and technological

mutations-on planning models to enhance the practical value and system anti-interference capability of the strategies.

On this basis, constructing a "policy-technology-market" tripartite dynamic collaborative analysis framework and combining long-cycle historical observation data will quantitatively verify the non-linear interactive effects among subsidy phase-outs, technological progress rates, and market endogenous demands, providing a scientific quantitative basis for dynamic policy adjustment. In addition, there is an urgent need to strengthen empirical exploration of user cognitive preferences, utilizing quantitative methods such as questionnaires and behavioral game experiments to analyze cognitive influencing factors and design targeted guidance strategies. Ultimately, by exploring the integrated application of cutting-edge technologies such as artificial intelligence and blockchain in intelligent facility operation and maintenance, distributed safety protection, and transparent user services, the innovative development potential of the industry can be further tapped, facilitating the comprehensive achievement of carbon neutrality strategic goals in the transportation sector.

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