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Review of Charging Station Siting and Sizing under Government Subsidies Considering Charging Demand Uncertainty

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ABSTRACT

Against the backdrop of global environmental and energy challenges, electric vehicles (EV) have emerged as a pivotal direction for transportation development owing to their low energy consumption and low pollution. However, EV adoption remains constrained by lagging infrastructure, particularly the difficulty of charging. The siting and sizing of charging stations (CS) has therefore become a critical research problem. Early studies focused on location models under deterministic charging demand; as research has deepened, scholars have begun to address demand uncertainty from perspectives including dynamic evolution, spatiotemporal uncertainty, and multi-factor variability, thereby making siting models more practically relevant. In the domain of government subsidy policy, research has affirmed the positive role of subsidies in EV markets and charging infrastructure, progressing from fiscal and tax policies that support industrial growth to in-depth examinations of subsidy forms and phases. Nevertheless, notable gaps persist: most studies rely on hypothetical scenarios, lack organic integration of siting, capacity planning, and subsidies, and inadequately account for operator interests. Future research must address these gaps to advance sustainable EV industry development and to construct an efficient and rational energy supply system for electric mobility.

KEYWORDS

Charging Station Planning; Demand Uncertainty; Government Subsidies.

1. INTRODUCTION

As production scales expand and energy resources dwindle, environmental and resource problems have become increasingly prominent. Transportation is a major pollution source, accounting for 12% of China's total carbon emissions, with automobiles contributing over 80%. EVs offer advantages including low energy consumption, high efficiency, low operating costs, and minimal environmental pollution. By 2025, China's EV fleet had reached 30.22 million, accounting for 68.74% of the new energy vehicle stock. China's EV sector has transitioned from a policy-driven to a market-driven stage, and further progress requires focused improvement of supporting infrastructure systems for new energy vehicles. In practice, users differ in their preferences for charging time and cost; CS planning should therefore account for user demand and incorporate multiple charger types. The high investment and long payback period characteristic of CS construction impede both station deployment and industry development. Government subsidies can reduce construction costs, stimulate investment，and improve the operational efficiency of charging facilities; integrating government subsidies into CS operations optimization can therefore better promote the development of the CS industry. The mechanisms by which subsidy policies are introduced and their effects on CS operations optimization remain underexplored in the current literature. The role of government

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subsidies in promoting CS operations optimization thus constitutes a topic warranting further investigation.

2. RESEARCH SIGNIFICANCE

2.1. Theoretical Significance

This review systematically organizes and integrates the intersection of CS siting and sizing with government subsidies at the theoretical and methodological levels. Regarding demand uncertainty, it systematically synthesizes quantitative methods for charging demand uncertainty in existing literature such as robust optimization, dynamic programming, and queuing theory revealing the applicability and limitations of different modeling tools in spatiotemporal demand forecasting, and providing a methodological classification framework and optimization directions for future research. Regarding government subsidies, this review breaks through the fragmented perspective of traditional scenario-based game analysis in the synergistic study of government subsidies and CS planning, constructing a three-dimensional theoretical framework linking "subsidy mechanism-siting decision-capacity allocation，"clarifying the pathways through which subsidy forms affect operator behavior and market equilibrium, and filling the gap in existing theory regarding endogenous policy modeling. Furthermore, through critical assessment of existing research deficiencies, this review proposes an integrated theoretical framework of "dynamic demand-phased subsidies-multi-agent interest equilibrium" providing theoretical support for future research to shift from static analysis to dynamic evolution and advancing the paradigm upgrade of CS planning from isolated optimization to systematic decision-making.

2.2. Practical Significance

This review provides actionable decision-making references and policy optimization pathways for governments, enterprises, and industry. Regarding demand uncertainty, by summarizing the mechanisms through which charging demand uncertainty affects siting deviation, it proposes planning recommendations based on elastic demand forecasting, which can effectively reduce the risk of supply-demand mismatch in charging facility layout and enhance the charging service resilience of urban transportation networks. Regarding government subsidies, the analysis of the phased characteristics and classification effects of subsidy policies provides a scientific basis for policymakers: in the initial stage of CS construction, high-proportion construction subsidies can attract enterprise investment; in the mature operational stage, shifting to operational subsidies based on charging volume or service efficiency can guide CSs toward high-demand areas, alleviating the structural contradiction of "excessive suburban construction and insufficient urban supply." This helps achieve the dual objectives of social benefit and market vitality, accelerating the coordinated development of EVs and charging infrastructure under the "dual carbon" goals. Through its bridging role between theory and practice, this review provides systematic solutions for building an efficient, equitable, and sustainable EV energy ecosystem.

3. CHARGING STATION SITING PROBLEMS CONSIDERING CHARGING DEMAND

In recent years, the Charging Station Location Problem (CSLP) has attracted extensive academic attention, with related research becoming increasingly abundant. Given the practical significance of CS planning, charging demand, as its core parameter, has become a key research topic for many scholars. Regarding charging demand, existing research findings are mainly concentrated in two aspects.

Under deterministic demand, charging demand is primarily predicted based on traffic flow data, EV ownership data, and user behavioral habits. Wang et al. (2023) argued that charging demand depends on charging mileage, range status, and user charging willingness, using transportation system statistical data as the basis for charging demand prediction. Zhou et al. (2022) constructed a siting model with total cost minimization as the objective, incorporating comprehensive economic costs and environmental costs, introducing carbon emission factors into environmental costs, and incorporating road curvature coefficients to calculate distances from demand points to charging stations. Zhao Shuqiang et al. (2016) used a two-step search algorithm to determine the distribution locations and optimal capacities of charging stations based on existing EV ownership and urban road information. Gulbahar et al. (2023) predicted future EV numbers on roads based on Turkish historical data by forecasting total vehicle sales and internal combustion engine vehicle sales logic, using the results as key inputs for facility siting models. Schoenberg, Sven et al. (2023) established a CS planning period based on driver historical data to plan optimal locations suitable for fast-charging and slow-charging stations. Zhang Linjuan et al. (2024) established a spatiotemporal distribution prediction model for EV charging loads using dynamic Dijkstra algorithm and Monte Carlo methods, introducing uncertain scenario sets into the capacity determination model to describe the uncertainty of users' dynamic charging demand.

The above studies, whether addressing single-agent CS planning or comprehensive multi-stakeholder coordinated optimization, were all conducted under deterministic charging demand conditions. However, EV ownership and user types determine that charging demand possesses variability and uncertainty; therefore, incorporating charging demand uncertainty into CSLP research better aligns with practical engineering needs.

Under demand uncertainty, scholars analyze demand changes through methods such as dynamic programming, queuing theory, robust optimization, genetic algorithms, and triangular fuzzy functions, while considering factors including travel chain data and demand characteristics. Yang Nan et al. (2023) divided planning into annual stages based on the dynamic evolution of EV ownership and the fact that CSs are not built all at once due to funding constraints, making charging demand prediction more consistent with dynamic evolution scenarios; they also considered CS renovation and expansion, improving capital utilization efficiency. Sungwoo Bae et al. (2012) recognized that charging demand exhibits uncertainty in both temporal and spatial dimensions, establishing a demand prediction model based on fluid dynamics traffic models and M/M/s queuing theory, and using averages and other methods to express charging demand uncertainty in the model. Li et al. (2022) addressed the siting problem of EV charging stations with wind and solar energy, establishing an annual total operating cost minimization objective under charging demand uncertainty, using polyline distances instead of Euclidean distances between EVs and charging stations in the case study. Lin Jianxin et al. (2024) considered the typicality and heterogeneity of charging demand under different land use types, constructing a CS planning model with system cost minimization as the objective and solving it using a robust optimization model. Wu et al. (2024) extended time-independent charging demand to time-dependent arrival quantities in a simulation model under uncertain urban-route charging demand, deriving a CS siting and optimization model. Gan et al. (2020) constructed distance penalty functions and waiting time penalty functions to express how charging demand varies with distance and waiting time, solving the model using genetic algorithms. Huang et al. (2020) considered charging demand to be stochastic, with demand elasticity related to congestion and charging prices, and established a model with profit maximization as the objective.

4. RESEARCH ON CHARGING STATIONS UNDER GOVERNMENT SUBSIDIES

Current research on government subsidies is mostly concentrated on the effects of government subsidies on EV enterprises and charging pile construction. Early research mainly focused on the

effects of government subsidies on EV enterprise innovation, industrial development, and consumption promotion. Zhao Ye et al. (2019) compared the effects of R&D subsidies, market subsidies, and mixed subsidies on market stability, concluding that R&D subsidies are optimal for enterprise innovation and provide the greatest improvement in market stability. Yang et al. (2019) argued that in market competition with traditional energy vehicles, the new energy vehicle industry requires government support. Chen Yongwei and Mu Dong (2018) argued that the higher consumers' recognition of EVs, the lower the efficiency of consumption subsidies.

As EV ownership increases, scholars have shifted their research focus to subsidies for EV charging stations. Research is mainly concentrated in three aspects: 1) Subsidies for EVs should gradually shift to subsidies for CS construction. Tang et al. (2022) argued that EV market development without public subsidies is challenging, and that subsidy incentive policies for charging infrastructure are currently limited, mainly taking the form of general subsidies. Zhang Yong et al. (2014) argued that in meeting customer demand, EVs produced and sold by automobile manufacturers do not exist in isolation but are complementary to many products. These complementary products include EV charging infrastructure separated from the vehicle. 2) The mechanisms through which operational subsidies and construction subsidies affect CS construction and operation. Chen et al. (2023) concluded that government provision of investment subsidies alone is optimal. Yue Weizhong et al. (2020) argued that the subsidy amount received by charging stations is positively correlated with the number of charging piles built. They concluded that government subsidies play a key role in promoting market establishment and development, recommending a classified subsidy mechanism based on the development level of CS operational scale, and that government should improve management efficiency to promote efficient use of subsidy funds. 3) Phased subsidies for CS enterprises. Ling Shuai et al. (2024) recommended dividing CS industry development into three stages for subsidies. In the initial stage of CS enterprise development, construction subsidies should be adopted; when CS operations reach a certain scale, subsidies can gradually shift from construction subsidies to operational subsidies; in the mature stage of the industry, subsidies can gradually be phased out. Zhang Linghong et al. (2023) recommended selectively implementing consumption subsidies and charging station subsidies based on EV sales volume. In the initial stage of EV industry development, when sales volume is low, the government should simultaneously implement consumption subsidies and charging station subsidies; as sales volume increases, the government can implement only charging station construction subsidies and further withdraw from charging station subsidies.

5. CRITICAL ASSESSMENT

Although the above literature has studied CS construction and subsidy forms from different perspectives, and can to some extent improve subsidy flexibility to reduce costs, the following deficiencies remain:

5.1. Limitations and Breakthroughs in Research Paradigms

Early CS siting and sizing research was mostly based on deterministic demand assumptions, relying on static parameters such as fixed traffic flow and EV ownership to construct optimization models. Although such models simplified computational complexity, they ignored the dynamism, randomness, and spatiotemporal heterogeneity of charging demand arising from user behavioral fluctuations and transportation network changes. In recent years, scholars have begun to introduce demand uncertainty analysis tools, such as robust optimization, queuing theory, and dynamic programming, attempting to quantify uncertainty through probability distributions, fuzzy functions, or elastic demand functions. However, existing research still has two major limitations: 1) Most models focus on only a single uncertainty dimension of time or space, lacking comprehensive research on “spatiotemporal coupling uncertainty.” 2) The coupling between demand prediction and siting models is insufficient, resulting

in planning outcomes with limited adaptability to actual scenarios. Future research needs to further integrate multi-source data such as real-time traffic and user preferences with machine learning techniques to construct a dynamic demand-responsive siting framework.

5.2. Disconnection between Subsidy Policy and Siting Planning

Government subsidies, as an important driving force for charging infrastructure construction, have policy effects mostly studied at the macro level of market penetration and industrial growth. For example, Zhao Ye et al. compared the effects of R&D subsidies and consumption subsidies through game models, and Tang et al. proposed that subsidies should gradually shift toward charging infrastructure. However, the integration of subsidy policies with siting and sizing models in existing literature remains weak: 1) Subsidies are mostly treated as exogenous parameters (such as fixed amounts or proportions), not internalized as core variables in siting decisions; 2) Quantitative analysis of the differentiated effects of subsidy forms (construction subsidies vs. operational subsidies) on operator behavior is lacking. For example, although Chen et al. [19] demonstrated the superiority of investment subsidies, they did not reveal how these subsidies change siting preferences through cost-benefit mechanisms. This review argues that a closed-loop model of "subsidy–demand–siting" must be constructed, dynamically linking subsidy policies with demand uncertainty and enterprise profit objectives, to analyze the micro-level mechanisms through which subsidies affect market equilibrium.

5.3. Lack of Multi-agent Interest Coordination

Existing CS planning research mostly aims at minimizing total social costs or maximizing service coverage, but neglects the economic rationality of operators as market entities. In reality, CS investment has characteristics of high sunk costs and long payback periods; if guided solely by social benefits, enterprise investment willingness may be suppressed. Some scholars have attempted to construct profit maximization models from the operator's perspective, but their assumptions (such as perfectly competitive markets) deviate from real-world contexts. Future research needs to incorporate a multi-agent game framework to coordinate the interests of government, operators, and users: for example, through contract design (such as linking subsidies to service quality) or differentiated pricing mechanisms (such as peak-valley electricity price subsidies), achieving Pareto improvements in both social benefits and enterprise profitability.

6. CONCLUSION

Driven by global energy transition and the "dual carbon" goals, EV charging station siting and sizing research has evolved from a single technical optimization problem into a complex systems engineering problem encompassing multi-dimensional coordination of technology, economics, policy, and society. Although current research has made significant progress in demand prediction, model construction, and policy design, facing rapidly iterating industrial demands and dynamically evolving policy environments, it is urgent to break disciplinary barriers and construct cross-domain theoretical frameworks and practical pathways.

6.1. Disciplinary Integration: From Isolated Optimization to Systematic Integration

CS planning is essentially a multi-objective, multi-constraint decision-making problem requiring the integration of operations research, policy science, data science, and other multidisciplinary methodologies. For example, operations research provides tools such as genetic algorithms and robust optimization for siting models, but the "black-boxing" of purely mathematical models may lead to insufficient policy sensitivity and social interpretability; policy science can analyze the economic effects of subsidy mechanisms but lacks quantitative support for technical feasibility. Future research needs to explore hybrid modeling paradigms oriented toward "technology-policy" synergy: for

example, embedding reinforcement learning into dynamic subsidy policy simulation, or using digital twin technology to construct "virtual cities" to test the long-term effects of different subsidy strategies. Additionally, the intervention of data science (such as multi-source heterogeneous data fusion and spatiotemporal big data mining) can improve the real-time performance and granularity of demand prediction, providing precise inputs for dynamic planning.

6.2. Theoretical Innovation: From Static Equilibrium to Dynamic Evolution

Existing research is mostly based on static equilibrium assumptions, treating charging demand, subsidy policies, and market structure as fixed parameters, which is difficult to adapt to the characteristics of the high-speed development stage of the EV industry. In fact, charging demand continuously evolves with technological progress (such as the popularization of ultra-fast charging technology), user habit migration (such as the rise of shared mobility models), and urban spatial restructuring (such as the promotion of TOD models); subsidy policies also need to be dynamically adjusted with industrial maturity. Therefore, theoretical models need to shift from "equilibrium analysis" to "evolutionary simulation," for example, constructing Agent-Based Modeling (ABM) frameworks to simulate the interactive behavior of government, operators, users, and other multi-agents in dynamic environments, revealing the chain effects of subsidy phase-out, demand fluctuations, and market competition. Such models can not only capture nonlinear evolutionary patterns but also deduce the synergistic pathways of "subsidy-technology-market"through policy sandboxes, providing forward-looking predictions for policy formulation.

6.3. Practical Breakthroughs: From Local Pilots to Global Adaptation

At the practical level, CS planning needs to balance standardization and differentiation. On the one hand, universal planning principles (such as the "demand density-subsidy intensity" matching criterion and the "investment-return-risk" balance threshold) should be distilled to form replicable and promotable standardized toolkits; on the other hand, regional differences should be respected, and classified adaptation strategies should be developed. For example, for high-density urban core areas, "land bundling subsidies" (such as linking charging station construction with commercial real estate development) can be adopted to enhance urban layout enthusiasm ;for remote areas, "photovoltaic-storage-charging integrated" microgrid models should be explored to reduce dependence on the main power grid. Additionally, synergistic innovation between "hard technology" and "soft institutions" needs to be strengthened: on the technology side, promote the application of V2G (Vehicle-to-Grid), smart orderly charging, and other technologies to enhance the flexibility of charging stations as distributed energy nodes; on the institutional side, explore market-based incentive tools such as carbon credit trading and green finance to construct a "policy-driven-market-pulled" dual-engine mechanism.

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