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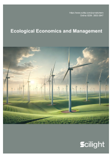

Article

Research on the Spillover Effects of Green Infrastructure: From the Perspectives of Market Structure, Spatial Governance, and Environmental Value of Charging Station Networks

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Abstract: Propelled by the urgent global context of sustainable development and China's "dual carbon" strategic goals, green infrastructure has emerged as the core of urban low-carbon transition. This analytical framework is used to study how it impacts urban carbon emission reduction. It provides new content on the existing green infrastructure theory and comes up with a new perspective on using station networks' to reduce carbon emissions. The study shows that the emission reduction effect of charging station networks depends not on quantity, but on the systemic linkage and collaborative promotion of three key aspects. First, changing the market structure from "oligopolistic scale competition" to "coexistence of a variety of ecosystems" leads to the deep integration of technology innovation and business model, which produces industrial and economic spillover effects. Secondly, optimizing spatial governance from an "efficiency-first" approach to a "balance between equity and efficiency" can reduce ineffective transportation emissions and improve service accessibility, thus creating social equity spillover value. Lastly, the increase in environmental value from "isolated electricity supply" to "system-integrated charging interaction" places the network as a major enabler of flexible grid regulation and renewable energy integration, achieving environmental spillover effects at the transportation-energy system level. By comparing domestic and foreign research and multiple city cases, this paper shows that only through the use of policy guidance and market mechanisms to promote the coordinated development of these three aspects can the multidimensional value of charging station networks as important green infrastructure be fully realized. This gives a vital theoretical basis and real path for cities to reach the full integration of transport and power systems and accomplish carbon neutral objectives.

Keywords: charging station network; green infrastructure; tripartite synergy; carbon emission reduction; spillover effects

1. Introduction

As the world moves rapidly toward its goal of carbon neutrality, China is enthusiastically embracing green development ideas, making the objectives of "peak carbon emissions and carbon neutrality", as well as the effective coordination of pollution reduction and carbon reduction, a significant national strategy. Therefore, developing green infrastructure has become an important way to promote the green and low-carbon transformation of the economy and society. As a necessary link between the energy revolution and the transportation revolution, the construction and development of the charging station network greatly influence the future of the new energy vehicle industry and have far-reaching and extensive spillover effects. In this study, spill-over effects refers to the unintended yet beneficial impacts generated by charging station networks that extend beyond their primary function of providing charging services. Specifically, it encompasses three dimensions. Industrial spillover, the stimulation of technological innovation and new business models through market structure optimization. Social spillover, the improvement of spatial accessibility and equity in urban mobility through optimized spatial governance, and Environmental spillover, the enhancement of grid flexibility and renewable energy integration through systemic energy interactions. These spillover effects transform charging stations from isolated infrastructure nodes into catalysts for urban low-carbon transition, creating multiplied carbon reduction values that exceed the sum of individual station effects. Spill-over effects include different areas such as market, space and environment, changing how we generate income, organize cities and handle nature. In recent years, the country has implemented a series of significant policies, giving us a clear direction and strong institutional support for the growth of green infrastructure. The 2025 Government Work Report further included "Coordinating the promotion of carbon reduction, pollution reduction, ecological expansion and economic growth, actively realizing all-round green transformation of the economy and society to deal with climate change and promote sustainable development" among the ten key tasks, thus defining the strategic position of green development. At the same time, the Guiding Opinions on Promoting the Integrated Development of Transportation and Energy, released by the Ministry of Transport together with the NDRC and other ten departments, provide more specific development goals. By 2027, a multi-departmental collaboration framework for the integration of transportation and energy will have been developed, with electricity accounting for 10% of the final use of energy in the transportation sector. Non-fossil energy generation installed capacity along transportation infrastructure corridors should not be less than 5 million kilowatts, and the production capacity of green fuels for transportation will be greatly improved. By 2035, an initial transportation energy consumption system will be formed, with clean and low-carbon energy consumption as the main feature, technological innovation as the main support, and green, intelligence, and efficient as the main guidance. Battery electric vehicles will be the main stream of new car sales, it can strongly support the construction of a powerful transportation network and a new energy system, implement national dual-carbon strategic decisions, and protect national energy security. This sets up a good institution for the development of charging stations and shows that this work is both advanced and useful. In this situation, a comprehensive investigation into how charging station networks can function as nodes linking energy and transport systems is both theoretically and practically important. Planning, layout, and operation management of the charging station network are not only important for national energy security and regional coordinated development, but also an important project for ecological and environmental governance.

Currently, domestic scholarship primarily focuses on three dimensions, adopting problem-oriented approaches to deal with the particular problems brought about by the quick growth of local green facilities. In contrast, international research puts more stress on theoretical and methodological innovations, constantly improving model creation and considering and enhancing planning paradigms [1]. But there are few studies that look at green infrastructure from the point of view of the charging station network and carefully examine how it affects carbon reductions. International research stresses the fair and inclusive nature of spatial arrangement [2]. For example, one study looked at where charging infrastructure was spread out by making a system with different parts about how easy it is to use, how good it works, and how convenient it is [3]. The latest research is becoming more and more interested in the effect of charging networks combined with renewable energy systems [4]. To incorporate distributed energy resources would help ease the burden of operation on the fast-charging station to the distribution grid and even avoid unnecessary upgrade of the grid. But the large-scale application of this technology is limited by many factors, such as slow grid connection standards, lack of battery deterioration compensation mechanism, and inadequate incentive for vehicle owners' participation. Environmental value, according to recent research, shows that such a combination reduces the workload of the distribution network and cuts down on the need for extra investments in grid enhancements that are not essential. And standardized development is also important to make sure that cars and chargers work well together, stay safe, and run smoothly [5].

The innovation of this article is that it takes the charging station network as the object of study. From a market structure, spatial governance and environmental value integrated view point, it builds up a "three-dimensional synergistic spillover" analysis framework. This method goes beyond the constraints of conventional one-sided investigations, revealing the organized and intricate nature of the carbon-cutting results linked to charging station networks. This framework both improves on existing theoretical research about green infrastructure and gives us a new way to look at how charging station networks cut down on carbon emissions. Descriptive statistics of cases in cities such as Beijing's municipal administrative center and Shenzhen show that when combined with low-carbon changes in market structure, cross-regional collaboration in spatial governance, and moving towards "ecological-energy integration" in terms of environmental value, charging station networks can make the carbon-reduction effect take a big jump from growing straight to going exponential. It is achieved by means of three main routes: technology spread, factor reorganization, and behavior modification. This study tries to create a complete analytical logic covering "big strategy, middle administration, small action" aspects, giving theory support and policy ideas for changing green infrastructure from just getting bigger to becoming better.

This study makes three primary contributions. First, theoretically, it constructs a novel 'three-dimensional synergistic spillover' analytical framework integrating market structure, spatial governance, and environmental value perspectives, extending green infrastructure theory beyond isolated technical assessments. Second, methodologically, it employs a mixed-methods comparative case study approach combining quantitative descriptive statistics with qualitative comparative analysis of domestic and international literature, identifying systemic linkage—rather than infrastructure quantity—as the key driver of carbon reduction. Third, empirically, it reveals three specific spillover mechanisms—technology diffusion through market diversification, factor reorganization through spatial optimization, and behavioral modification through environmental value enhancement—demonstrating that charging networks achieve exponential carbon reduction effects when the three dimensions are synergistically coordinated.

This article advances green infrastructure research through three specific contributions. Theoretical contribution, existing literature treats charging infrastructure as technical installations or isolated economic assets, this study reconceptualizes them as socio-technical systems where market organization, spatial configuration, and energy interactions co-evolve. The 'three-dimensional synergistic spillover' framework provides the first integrated analytical lens that explicitly links these three domains. Methodological contribution, this research employs a multi-dimensional comparative case study design combining. Quantitative descriptive analysis of carbon reduction outcomes. Qualitative comparative analysis of domestic vs. international literature to identify context-specific mechanisms, and mechanism-based theorization deriving three causal pathways from empirical patterns. Practical contribution: The framework translates into actionable policy instruments with quantified targets grounded in empirical evidence.

2. Literature Review

2.1. Current State of Domestic Research

Under the macro background of global energy transition and the "dual-carbon" goal, green mobility infrastructure, especially the electric vehicle charging station network, is gradually becoming an important part that is changing the urban spatial, market, and environmental landscape [6]. Domestic scholars' study on its spillover effect has developed from single-discipline technical-economy analysis to all-round interdisciplinary exploration including market structure, spatial governance, and environmental value.

From the perspective of market structure, China's charging pile operation business has formed a clear oligopolistic competition situation [7], with the top three companies, TELD, StarCharge, and State Grid Corporation of China, becoming the main force in the market. Leading enterprises have set up a 3D integrated operation model of "charging network-microgrid coordination-virtual power plant aggregation", achieving smart management and control over more than one million charging devices, highlighting the benefits of economies of scale and scope [8]. This kind of operation model can help people make use of their resources better when they need to do something important. It can also save money by buying lots of things together. At a certain point in time, it helps concentrate the distribution of resources and achieve economies of scale, thus promoting the improvement of industry technical standards and the optimization of the entire service system [9]. But we shouldn't ignore its possible bad results—too much power in one place might stop little and medium businesses from having new ideas, make markets less colorful and lively, and in the end, change how industries grow over time [10].

Industrial policies are also an important part of the development of the new energy vehicle industry [11]. Zhou Yahong's research [12] shows that supportive policies can help with innovation, and he says that kind of support is important for new industries when it comes to setting up the market structure. Subsidy policies and entry standards accelerate the growth process and improve resource coordination. The government needs to properly control the strength and boundaries of their own intervention, and guide the market signals correctly, so as to improve the self-development mechanism of the industry [13]. Vehicle purchase subsidies were given to activate private consumption demand, construction subsidies were provided to reduce the investment barriers for public charging station, and operating incentives were offered to guarantee steady operator incomes, creating powerful policy signals that led to a great deal of capital flowing into the charging pile sector. And then this big money makes companies put more money into finding new ideas, so new techs such as fast-charge power and smart order charging can appear quicker, shortening how long and where you need to wait to charge your car [14]. Technology maturity also encourages deep cooperation between charging pile companies, auto makers, and power grids, making it possible to have a unified charging service platform and data exchange system. This has created a virtuous cycle of "policy guidance—capital aggregation—technological iteration" [15], promoting new models such as "charging pile companies + vehicle manufacturers + power grid" collaborative operation and platformized charging services.

At the spatial governance level, Domestic studies mainly focus on spatial justice, topological mismatch and equitable coverage of charging piles network [16]. About the present situation of new energy vehicle development, disclosed the distribution characteristics of innovation in the new energy vehicle industry through ArcGIS and HLM to make maps and analyses [17]. This shows the contrast in how people in the Pearl River Delta pursue new innovations alone or as a team, and collaborative efforts in the region are not yet adequate. Welch's [18] "Transportation Equity" analytical framework and domestic research into public transport accessibility in subsidised housing provide a model for assessing spatial justice within the charging pile sector. Research states that spatial justice has three parts: Opportunity equity protects every group's equal chance to pick green travel; Cost equity stops wrong moving of building and running costs to poor neighborhoods; Procedure equity takes into account what poor groups want when picking places [19]. Presently, the domestic charging pile layout does not sufficiently take into account regional development disparities, causing developmental injustice because of spatial mismatch and distributive injustice due to a lack of charging piles in older residential areas [20].

"Topological Mismatch" is derived from the research on job-housing balance, referring to the inconsistency between the connection of network nodes and the actual demand flow pattern [21]. Studies have shown that the charging pile network has three mismatches: spatial topological mismatch, which indicates that the locations of charging stations do not correspond to the number of cars and driving patterns; network topological mismatch, indicating that the power grid and communication network cannot support all the charging stations required; and functional topological mismatch, indicating that there are insufficient fast chargers for those traveling long distances and inadequate slow chargers for those merely parking their vehicles. Therefore, China's charging pile network changes from "supply and demand misalignment" to "network structure imbalance" [22], and the main contradiction of "fair coverage" is revealed by the obvious urban-rural dual structure [23]. As of June 2025, the coverage rate of charging facilities in China at the county level is 97.08%, at the township level is 80.02%, and at the village level is about 18%. From city to countryside, the "coverage gradient" is the most vulnerable point to achieve fair coverage [24]. Through research it was discovered that both policies and markets must work together to create true equity in coverage [25].

The equity-efficiency tension in charging infrastructure governance has traditionally been framed as a static optimization problem, yet empirical evidence suggests this relationship evolves fundamentally across development stages. Drawing on welfare economics and evolutionary planning theory, we propose a stage-differentiated governance framework that specifies how governments should sequentially prioritize objectives and allocate resources as infrastructure matures from nascent networks to comprehensive systems.

During the foundational phase characterized by coverage rates below 30%, severe infrastructure shortage and private sector risk aversion create conditions where efficiency maximization must take precedence. Governments should concentrate scarce public resources in high-demand corridors—central business districts and major transportation arteries—to demonstrate network viability, achieve utilization thresholds above 15% that attract commercial investment, and establish technical interoperability standards. Equity considerations at this stage are necessarily constrained to basic universal service obligations ensuring no administrative district remains entirely unserved, with uneven spatial distribution accepted as a temporary cost of rapid scaling.

The optimization phase emerging at 30–70% coverage marks a critical transition where governance priorities become more differentiated. As core urban areas achieve adequate service levels, "charging deserts" in peripheral and older neighborhoods become politically salient while accumulated operational data enable precision planning. This phase demands sophisticated resource allocation that identifies synergistic opportunities—correcting topological mismatches where station relocation simultaneously improves accessibility for underserved communities and reduces system-wide search congestion. The equity-efficiency relationship shifts from trade-off to potential complementarity, supported by tools such as "charging demand heat maps" that reveal latent demand in disadvantaged areas and cross-subsidization mechanisms allowing profitable urban stations to fund rural extension.

Refinement phase governance at coverage exceeding 70% centers on equity-centered quality standards and system integration. With basic access nearly universal, priorities shift to ensuring "15-min charging zones" for 90% of population, mandatory accessibility provisions for disabled users, and protection of "last mile" rural coverage against commercial withdrawal. Simultaneously, mature networks must optimize environmental value through V2G integration and renewable energy absorption. China's current policy trajectory—from the "quantity-first" targets of 2015–2020 toward the "quality and equity" emphasis in the 14th Five-Year Plan—exemplifies this framework's empirical relevance, reflecting transition from Phase 1 to Phase 2 as county-level coverage approaches saturation while village-level access remains below 20%.

Environmental value point of view, the charging pile network is seen as important infrastructure to promote the low-carbon transformation of the transportation industry. Domestic researches on this issue mainly revolve around three major aspects: reducing emission effect, energy synergy, and complete life cycle impact. Studies indicate that regarding the carbon emission reduction effect, it is focused on the immediate "charging—emission reduction" connection. Emissions reductions happen with combined solar (CS) and distributed renewable energy sources [26]. Some scholars have also mentioned that carbon emissions have regional differences, higher in the east and lower in the west, which is caused by different types of electricity used, and new models applied in certain situations can improve carbon reduction intensity. Energy Synergy field: Integrated Photovoltaic-Storage-Charging Systems and Vehicle-to-Grid (V2G) Technology have become focal points [27]. The former can cut carbon emissions per kilowatt-hour by 51%, and the latter allows for grid peak shaving and valley filling, improves the utilization rate of clean energy, and through smart scheduling, reduces the impact on the grid and the demand for fossil fuels. Full lifecycle studies use the LCA method [28] to look at how charging piles affect the environment from getting raw materials, making equipment, using and taking care of them, and what happens when they're no longer needed. The study centers on land usage, the consumption of significant metal resources such as copper and aluminum, and localized ecological disruptions during the construction and production stages. Also addresses some major environmental governance concerns during the decommissioning phase, such as equipment disassembly, classification and reuse of electronic parts, and harmless disposal of heavy metals.

2.2. Current State of Overseas Research

Overseas studies on charging pile networks, according to the background of global energy transformation and different regional development patterns, show that there are some important features such as "regional cooperation, technological power, and institutional creation". It has created a research system with three dimensions: improving market structure, improving spatial management, and enhancing environmental worth.

Focuses on markets outside the country, urbanization increases the demand for urban green infrastructure (GI) which helps people who live in cities and allows for sustainable planning methods. To improve the market structure of overseas charging pile networks, we need to find a balance between equity and accessibility. As with the domestic situation, international studies also show that there are similar spatial distribution inequalities for charging infrastructure, too much concentration in the central business district and too little coverage in high-density residential areas [29]. This is known as "charging deserts" by experts. Such a form of spatial inequality can make it difficult for people in certain areas to utilize green electric vehicles. It makes the gap wider between how much money different groups have for driving around in cars. Poorer neighborhoods get more pollution from cars because they don't have as many nice clean ways to go places, so these neighborhoods suffer even more than others when everyone starts using greener ways to move around [30]. Therefore, scholars believe that the planning of charging facilities and the investment decision-making of market entities should be "taking into account the range of coverage as well as demand prediction" [31]. Coverage scope contains the idea of fairness within itself. In addition to forecasting demands, infrastructures planning should focus on its coverage more. Market planning should pay attention to both efficiency and accessibility. The equity-efficiency balance evolves from a zero-sum trade-off to synergistic complementarity as the system matures. Early-stage efficiency investments create the technological and financial foundations for later equity expansion. Shenzhen's profitable urban networks subsidizing rural extension, while late-stage equity improvements enhance overall system efficiency by reducing 'search congestion' and improving load distribution.

Spatial governance: International researches are moving toward data-driven planning of charging infrastructure rather than relying on experience, using data-driven techniques such as K-Means spatial clustering [32] to improve the location of charging stations. In particular, scholars take many different types of information together—places of interest (POI), mobility trajectories, grid load, and land use—to make maps that show where services might be needed, finding out which parts don't have enough help. But existing models are also reflecting on their methods. Scholars state that many prediction models operate on large areas such as towns or cities, hence when these models look down upon these areas, smaller places become difficult to discern. These models are generally based on how people charge their cars, but they don't consider the limitations of that charging [33]. It means that the past charging record data can only show the charging behavior pattern of the current user, but cannot reflect the hidden demand of potential buyers. Take for example someone who does not buy an EV due to the inconvenience of charging, this person will never show up in the data. In order to do so, new studies are making planning models more dynamic and detailed by using information from social networks to determine how much different groups want to charge their cars secretly [34] in hopes of getting people to charge their cars more.

In terms of environmental values, the international research puts great stress on the integration of charging networks with RE deployment [35] to get true environmental benefits. Researchers support the combined "solar-storage-charging" model, involving the use of distributed photovoltaic and energy storage systems at charging stations. This method lightens the load on the power grid by using local consumption and microgrids, and it uses LCA methods to count all the carbon saved during the whole process of making electricity, sending it, and then charging up, so we don't move the bad parts of the environment to where we make our electricity. At the same time, V2G technology is being talked about quite a lot, and it's seen as a big help for making the grid more flexible and able to use variable renewable energy. V2G can not only do peak shaving, valley filling, but also provide some auxiliary services such as frequency regulation by managing the charge and discharge of electric vehicle clusters, and it is considered as a "mobile energy storage asset" that can greatly improve the grid's ability to absorb wind and solar power. But many studies show that applying this tech on a large scale has some limits because there are problems with how the power grid connects, no way to fix batteries when they get old, and not enough reason for people who own cars to get involved [36].

2.3. Comparative Analysis of Domestic and International Research

The distinct research orientations between domestic and international scholarship on charging infrastructure do not emerge randomly but reflect deep structural differences in institutional environments, developmental stages, and governance logics. Understanding these underlying mechanisms is essential for contextualizing research findings and avoiding inappropriate policy transplantation.

First, the policy environment shapes research priorities through divergent state-market relationships. China's charging infrastructure development operates within a 'campaign-style governance' framework, characterized by centralized target-setting, such as the 2027 and 2035 milestones in the Guiding Opinions, massive fiscal mobilization, and state-owned enterprise leadership. This creates a research imperative focused on policy implementation efficiency, industrial coordination, and rapid scaling mechanisms. Conversely, international markets rely on 'regulatory market-making' through emission standards, carbon pricing, and private capital incentives, generating research interest in market failure correction, behavioral incentives, and cost-benefit optimization under budget constraints.

Second, market maturity determines the phase-specific research agenda. China's EV market has entered the 'mass diffusion phase', with research shifting from adoption barriers to system optimization, grid integration, and cross-sector coordination. Most international markets remain in the 'early adoption phase', where infrastructure-vehicle coordination dilemmas, consumer acceptance, and initial network planning dominate academic inquiry. This phase difference explains why domestic studies emphasize 'topological mismatch correction' while international research prioritizes 'demand forecasting' and 'siting optimization'.

Third, data regimes and research infrastructure create methodological path dependencies. China's centralized administrative system generates comprehensive operational data from state-owned grid companies and large operators, facilitating empirical studies on grid integration, technical performance, and system-level optimization. However, commercial confidentiality restrictions and fragmented departmental data silos limit access to granular spatial usage patterns, constraining micro-level equity research. International contexts benefit from more open data policies, academic-industry partnerships, and longitudinal household surveys, enabling sophisticated spatial analysis, user behavior modeling, and stated preference studies, but often lack system-level operational data for assessing grid-scale impacts.

Fourth, the environmental regulatory framework creates divergent valuation methodologies. China's 'dual carbon' targets generate urgency for quantifying direct emission reductions, renewable energy integration rates, and immediate grid stability impacts at the national level. International research, operating within more mature carbon accounting systems and stronger environmental litigation frameworks, increasingly focuses on lifecycle assessment, distributional environmental justice, and indirect land-use effects. These differences explain why domestic studies emphasize 'PV-storage-charging' technical integration while international scholarship prioritizes 'charging desert' identification and accessibility equity.

Domestic research on charging pile networks mainly focuses on problems that arise due to the fast growth of local green infrastructure. On the contrary, international studies give more weight to theoretical and methodological innovations, constantly improving the reflection and optimization of model building and planning concepts.

Driven by China's huge market size and strong support from the government, a special "regulatory oligopoly" has formed [37]. Leading operators have considerable market shares; market structure analysis pays more attention to scale effects and industrial policies. It stresses that too much concentration of market power might result in a loss of innovative vigor among small and medium-sized companies, lessen the variety and dynamism of market rivalry, and even influence the healthy development of the whole business. Fairness in deployment, technological inclusivity, and needs of segmented markets are now becoming an important starting point for international studies to fix market problems. Fairness dimension stresses that low-income families, multiple family homes, and car-free families should not be excluded from the green transition via "fairness effect assessments" and "quotas for disadvantaged groups". Technological inclusivity means taking away digital and physical barriers, giving different levels of power to fit various kinds of cars and how much electricity the grid can handle. Identify the demands of segmented markets and move towards specific scenarios and precise allocation instead of a one-size-fits-all approach. This kind of all-around thinking represents a change in the way the market is structured from just being about making things work well to including everyone, being accurate, and lasting over time [38]. In terms of spatial governance, domestic studies mainly focus on issues such as spatial justice, topological mismatch, and equitable coverage. Analysis centers around the three aspects of spatial justice, equity of opportunity, cost justice, and procedural justice, and the three mismatches in charging piles, namely spatial topological mismatch, network topological mismatch, and function topological mismatch, as well as the main contradiction of "fair coverage". To the contrary, international studies focus on the method more, using a lot of standard models such as clustering algorithm and demand forecast, and systematically researching the applicable boundaries of these models to enhance planning efficiency. To be more specific, scholars don't just use data-driven approaches such as K-means spatial clustering [39] to improve the placement of charging stations; they also employ machine learning models that include various kinds of information such as POI [40], trajectories, and grid loads for better forecasts. Also, at the same time, they are thinking about the limits and conditions of these models. Environmentally, most domestic studies revolve around reducing emissions, energy synergy, and lifecycle impacts, focusing on grid stability risk alerts and the technical feasibility of V2G technology. International research is more systematic, it looks into how charging infrastructure can be optimized together with renewable energy, and creates matching market trading systems and price signals. Making sure that tech, econ, and pol work well together so the green change gets more benefits [41].

It is clear that there are considerable differences in research on charging infrastructure among domestic and international contexts: domestic studies center on local industrial scale and economic impacts, depending on big data for empirical investigation of spatiotemporal patterns, prioritizing grid stability and engineering execution. Conversely, foreign research stresses the creation of new theoretical paradigms, looks at planning limits using standard models, and includes ideas about fairness, tech inclusiveness, divided markets, and market system planning when designing charging station networks. As shown in Figure 1 below, the research framework and Table 1 Comparison of domestic and international research differences.

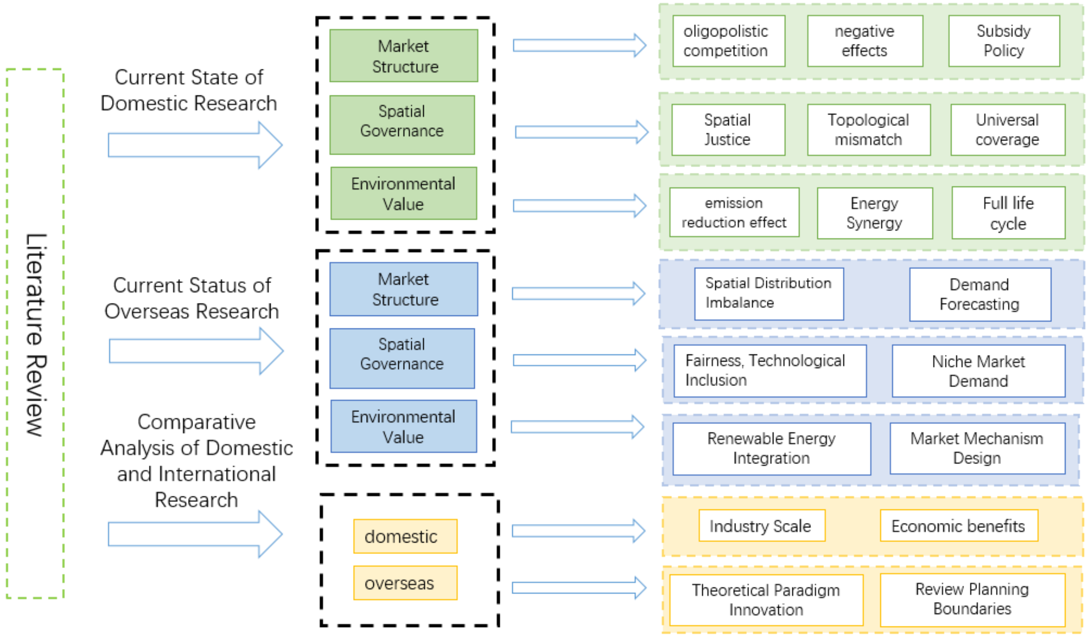

Figure 1. Research framework.

Table 1. Comparison of domestic and international research differences.

Dimension	Domestic Focus	International Focus	Institutional Driver
Market Structure	Scale effects, industrial policy	Equity, accessibility	Campaign governance vs. Regulatory market-making
Spatial Governance	Topological mismatch correction	Demand forecasting, data-driven planning	Rapid expansion vs. Organic growth
Environmental Value	Grid stability, renewable integration	Life cycle assessment, environmental justice	Dual carbon urgency vs. Mature carbon accounting

2.4. Literature Review

Market structure-wise, the highly concentrated market setting makes it hard for people to get research info. Operators hide the regional operations under the banner of commercial confidentiality, so it's tough to spot how much the environment is worth in different places that have different amounts of money. Furthermore, the layout strategy of oligopolistic enterprises inherently favors high-return areas, leading to a systematic deficiency of environmental benefit data for charging piles in secondary cities and rural areas, thus increasing the difficulty of studying regional differences. In terms of spatial governance, the difference between government-led and market-led governance models has an impact on the consistency of evaluation criteria. Policy document-specified "uniform reporting" data requirements do not fit well with the detailed academic research demands, and the lack of cross-regional governance coordination mechanism causes confusion over the scope definition for environmental value accounting. Also, there are many governance bodies causing responsibility to be divided up, so important information such as the rate at which decommissioned piles are recovered is left out of the assessment, and this also fragments the life cycle assessment. From an environmental value research standpoint, there isn't enough depth to the study of regional heterogeneity, and there isn't enough differentiation made about how to realize environmental value depending on the kinds of resources available and the level of development in those regions. Life cycle assessments are frequently limited, concentrating solely on certain stages or specific environmental elements, without fully taking into account all sorts of effects on land, energy, water sources, etc. And also, the incomplete data due to the lack of industry stats. Furthermore, the lack of standardization in research valuations adds to the problem because different carbon reduction accounting techniques and environmental value measurement units cause trouble when comparing outcomes from various studies.

3. Theoretical Research

To illustrate the synergistic relationships among the three dimensions, we propose a 'Three-Dimensional Synergistic Spillover' analytical framework as shown in Figure 2 below. This framework demonstrates how market structure, spatial governance, and environmental value interact to produce multiplied carbon reduction effects.

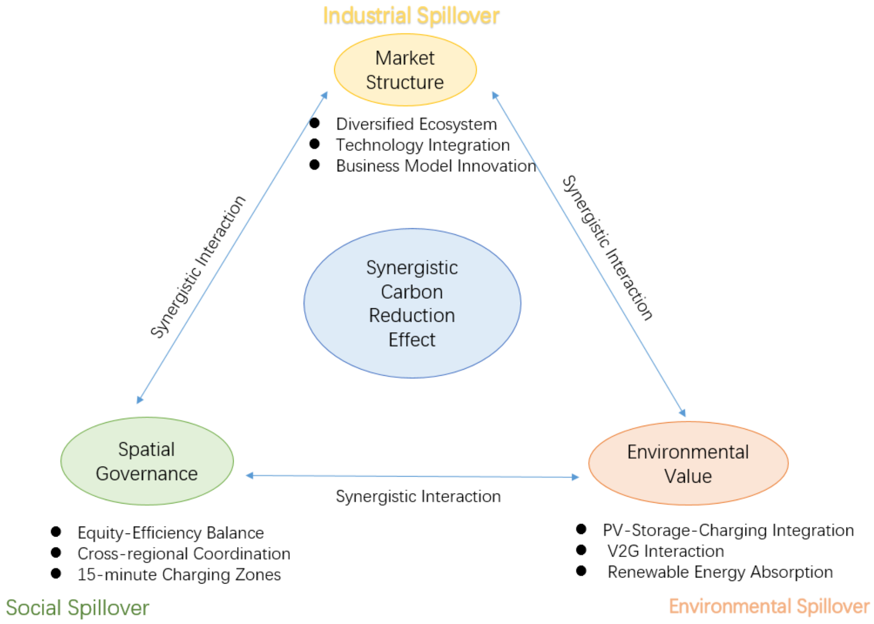

Figure 2. Three-dimensional relationship.

As shown in Figure 2, the three dimensions form a mutually reinforcing system. Market structure diversification provides technological and economic foundations for spatial governance optimization, while spatial governance creates the physical conditions for environmental value realization. Environmental value enhancement, in turn, feeds back to market structure through new business opportunities such as carbon trading and green electricity certification. This triangular interaction creates a positive feedback loop that amplifies the overall carbon reduction effect beyond linear addition.

Green infrastructure plays a significant part in cutting down on the environmental pollution brought about by economic activities. Driving innovation, promoting green development, which fits the concept of sustainable development [42]. After doing lots of research on both home and foreign markets, how places are run, and nature's worth, charging piles networks have grown past their old meaning of regular buildings. They are becoming clearer as green infrastructure for making urban ecosystems better and using energy more efficiently [43]. Charging pile networks' contributions to urban carbon reduction are not merely adding up numbers; rather, they involve a system that makes the market structure, space arrangement, and environmental conditions all work together and improve simultaneously. And such changes are causing the transformation of the charging pile network from points to a networked structure with important nodes linked to the city system to enhance the carbon reduction effect through multiple channels [44].

Market structure becomes more varied, which leads to technology integration because people who run the markets change from just a few companies doing things together to groups working together including government owned businesses, private companies, and places where people work. These different entities competing against each other helps bring "photovoltaic-storage-charging" techs together and encourages new ways of doing things [45], making it so that putting your car on charge doesn't make as much carbon. Urgency of carbon reduction requires the wide application of electric vehicles, and the planning of charging station locations is important for alleviating range anxiety and promoting the use of green energy [46]. Spatial layouts have changed from a focus on efficiency and urban core areas to one that balances equity and efficiency, covering both urban and rural areas, and precisely meeting the needs of various usage scenarios. This kind of change can lower extra transport emissions brought about by difficult trips, helping cut down on emissions coming from how people move around by making better choices about traveling. And it also promotes the coordinated planning between charging facilities, parking spaces, grids and renewable energies, thus forming the optimal layout of cross-administrative "15-min charging zones", and avoiding the redundant construction and misallocation of resources [47]. As the idea of energy system synergy gets stronger, how we see the good things for the environment changes from just thinking about replacing oil with electricity to seeing charging piles working better with small solar panels, storing energy, and connecting to the big power lines. Such a systemic integration does not only break the isolation of charging facilities, but also makes charging networks turn from mere energy users into "smart controllers" of the energy system. When there is too much green electricity, they absorb it and send it back to the grid when there is a lot of demand, this helps to balance the load on the grid, supports the use of renewable energy, and increases the benefits of reduced emissions not only from cars but from the entire energy system. It creates a multiplied carbon reduction value [48] and achieves synergistic environmental improvement through systematic integration and cooperation.

The environmental value of charging station networks manifests through three technical pathways that quantifiably contribute to carbon reduction and grid stability:

(1) Distributed Renewable Energy Integration: Photovoltaic-storage-charging integrated systems can reduce carbon emissions per kilowatt-hour by approximately 51% compared to grid-average electricity. Specifically, distributed photovoltaic systems installed at charging stations typically operate at 15–20% capacity utilization in urban environments, with each 100 kWp installation generating 150–200 MWh annually. When combined with 2–4 h battery storage systems, these facilities can achieve self-consumption rates exceeding 70%, reducing reliance on coal-dominated grid electricity during peak charging periods.

(2) Vehicle-to-Grid Grid Stabilization: V2G technology transforms EVs into mobile energy storage assets. Technical studies demonstrate that a single EV with 60 kWh battery capacity can provide 10–20 kW of grid regulation power, with daily bidirectional energy flow of 10–30 kWh. At the network level, Shenzhen's pilot program shows that 760+ participating stations can collectively absorb 88,000 kWh of excess renewable energy and discharge during peak demand, equivalent to providing 20–30 MW of virtual spinning reserve capacity. This flexibility service reduces the need for fossil fuel peaking plants, with each MWh of V2G-mediated energy transfer avoiding approximately 0.4–0.6 tons of CO_2 emissions compared to coal-fired peaking generation.

(3) System-Level Load Optimization: Smart charging algorithms that coordinate charging schedules with renewable energy availability can increase wind and solar curtailment absorption by 15–25%. By shifting charging loads to periods of high renewable generation, charging networks effectively act as demand-side management tools. The technical implementation involves predictive control systems that integrate weather

forecasting, traffic pattern analysis, and real-time electricity market signals. This systemic integration enables charging networks to function as ‘virtual power plants’, providing frequency regulation response times under 4 s and voltage support capabilities that enhance grid stability in distribution networks with high renewable penetration.

4. Case Studies

The two cities below have different characteristics in their development of charging piles networks, which are used as specific examples to show how the above-mentioned theories work in practice.

4.1. City 1: Beijing Sub-Center

The Figure 3 below shows the line chart of CO_2 emissions in Beijing’s sub-center (Tongzhou District) from 2012 to 2023, which indicates that CO_2 emissions are rising. As shown in Figure 3 below.

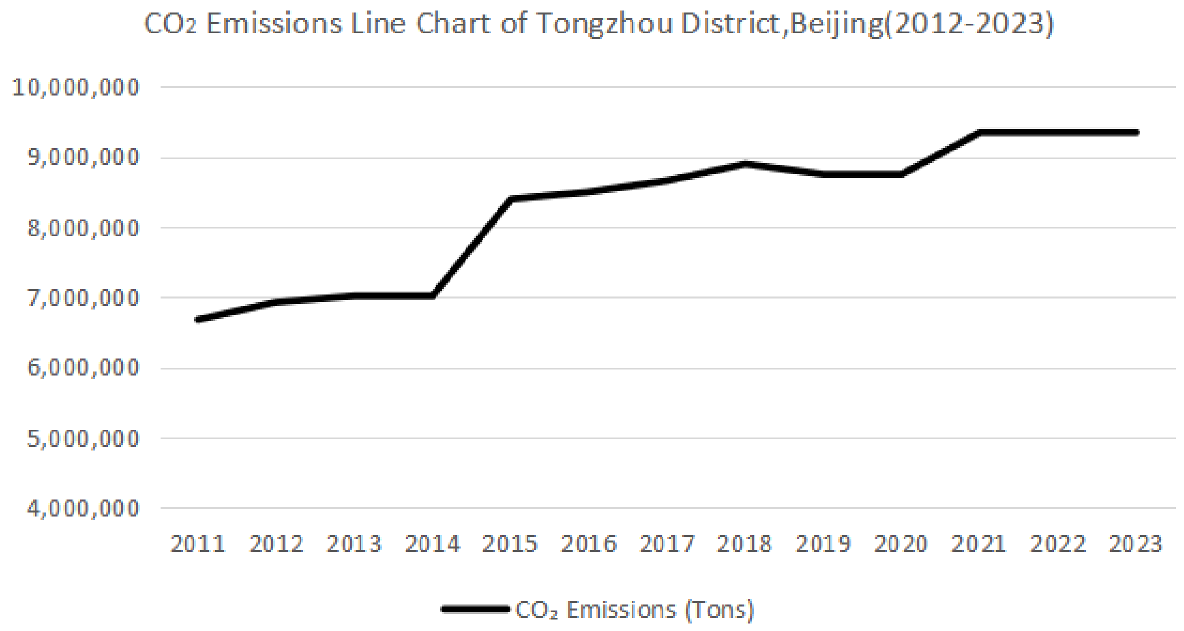

Figure 3. CO_2 emissions line chart of Tongzhou District, Beijing (2012–2023).

To quantitatively assess the initial outcomes of Beijing’s sub-center in its green and low-carbon transition, this study compiled and conducted descriptive statistical analysis on currently available data of key carbon reduction projects. The Table 2 below presents the key statistical indicators of each emission reduction project:

Table 2. Key statistical indicators for emission reduction projects.

Project Name	Key Indicators	Unit	Numerical Value (X)	$(X - \mu)^2$
Rural Coal-to-Electricity Conversion Project	Annual carbon dioxide emissions reduction	10 k tons/year	100.15	2504.452
Qiantuan Village “Zero-Carbon Community” Smart Microgrid	Annual carbon dioxide emissions reduction	10 k tons/year	0.061	2504.452
Sample Size (N)	Annual CO_2 Reduction		2	
Mean (μ)			50.1055	
Sum (ΣX)			100.21	
Standard Deviation (σ)			50.04	
Coefficient of Variation (CV)			0.999	

Note: Variance calculation process is $\Sigma(X - \mu)^2/(N) = (2504.452 + 2504.452)/2 = 2504.452$. Standard Deviation (σ) is the square root of the variance, which is $\sqrt{2504.452} \approx 50.04$. Coefficient of variation (CV) = $\sigma/\mu = 50.04/50.1055 \approx 0.999$.

The two projects covered by this analysis have together reduced CO_2 emissions by 1,002,100 metric tons annually (ΣX), which is quite significant; it initially indicates that replacing energy and developing a distributed energy system in the sub-center has some good effects on the environment.

Coefficient of Variation (CV = 0.999) which is close to 1 also shows that the data has quite a lot of spread. It means that the numbers inside the sample do not stay together near the average number; instead, they have big differences because there are some special cases called “coal-to-electricity” projects. Policy wise, it shows different ways to reduce emissions.

4.2. City 2: Shenzhen, Guangdong Province

The following Figure 4 gives a scatter plot (or bar chart) of Guangdong province’s power generation from 2012–2023. Nuclear power generation is the main one, and hydropower generation is decreasing every year. Wind and solar power generation is continuously growing, and the percentage of new energy power generation among all electricity production is also rising.

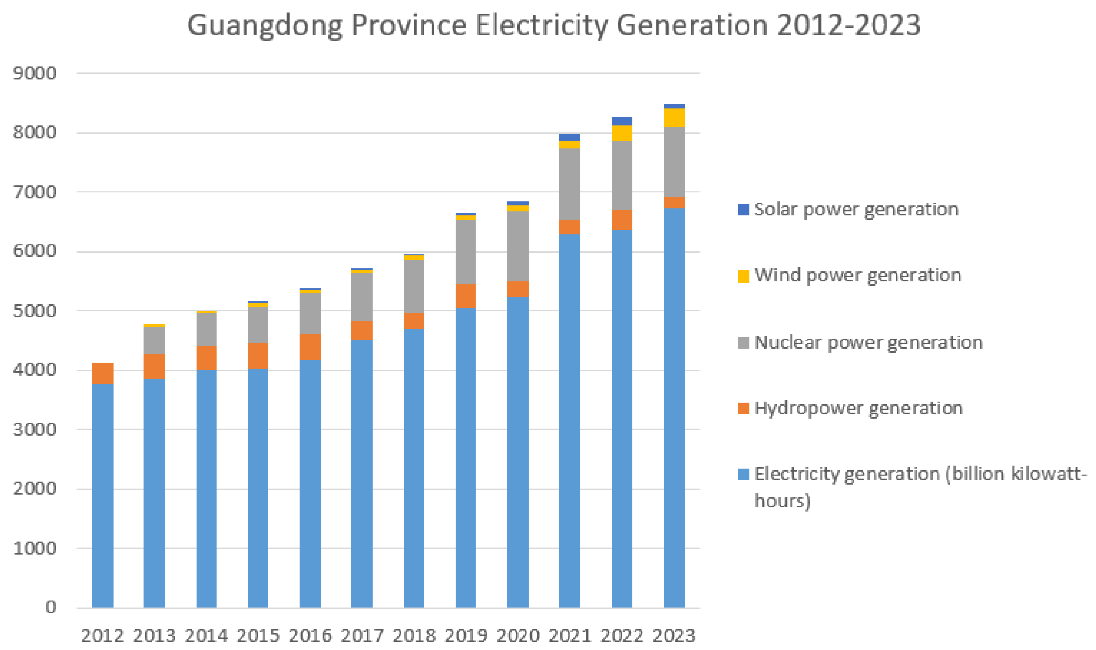

Figure 4. Guangdong province electricity generation 2012–2023.

Shenzhen is building itself into a “Supercharging City” and speeding up the creation of an “integrated city-wide charging network”. Installed clean energy capacity share has reached 78.7%, which provides a solid basis for “charging new energy vehicles with new energy electricity”. The Table 3 below summarizes the progress and carbon reduction results of Shenzhen in four main areas: charging facilities, clean energy, near-zero-carbon communities, and vehicle-grid interaction.

Table 3. Progress in core areas and carbon reduction outcomes.

Statistical Dimension	Data Item	Value
Charging Infrastructure	Total Number of Charging Piles	Over 487,000 (As of the end of June 2025)
	Number of Supercharging Stations	1057 stations (As of the end of June 2025)
	Rated Power per Supercharging Gun	Not less than 480 kW
Clean Energy Proportion	Share of Clean Energy Installed Capacity	Exceeds 80% (2024 data)
Near-Zero Carbon Community	PV Installed Capacity in Gaoqiao Community	536,000 WP (536 kWp)
	Annual Carbon Reduction from PV in Gaoqiao Community	420 tons/year
	Carbon Reduction per Unit of Electricity Generated	Approx. 0.78 kg CO_2/kWh
	Citywide Near-Zero Carbon Emission Pilot Zones	113 (as of the end of 2024)
Vehicle-to-Grid	Participating Test Stations/Charging Piles	Over 760 stations, 18,000 charging points
	Participating Test Trains	Over 17,000 train trips
	Total Interactive Electricity	88,000 kWh
	Single-Station Discharge Record (Lianhuashan Station)	Exceeded 13,000 kWh in a single day

Shenzhen’s experience shows that urban carbon reduction is not a breakthrough of a single technology, but a comprehensive project involving market, space, technology, and policy. By integrating all these methods: “Improving the charging station location layout—guaranteeing a clean power supply—establishing models similar to near-zero-carbon communities—energizing interaction systems such as V2G”, Shenzhen has turned their new energy vehicle infrastructure into a key center for its carbon neutralization efforts. And it has given out the precious "Shenzhen Model" for the green and low-carbon change of different big cities around the world.

Summarizing the practices of those cities, the ways that charging pile networks help reduce carbon can be clearly summarized as follows: Firstly, cut off carbon at its root by encouraging greener power supplies, such as Beijing's sub-center introducing a market mechanism that buys green electricity from outside sources directly reduces carbon produced during energy creation; Secondly, improving the efficiency of the energy system through systematic synergy, using key technologies such as V2G, charging stations can be turned into large-scale distributed energy storage systems. Participating in the grid peak regulation, adjusting the power supply and demand balance, and improving the overall operation efficiency of the power system can also bring about extra emission reduction opportunities at the level of systemic synergy.

5. Conclusions and Recommendations

5.1. Conclusions

In the end, this research concludes that what charging pile networks bring to urban carbon reduction is essentially a new way of thinking about things—one that shifts from mere quantitative growth, to systematic synergy, where all components fit together nicely. The emission reduction effect of such emission reduction effect is not just because there are many charging piles, but rather due to the deep integration and development among three important aspects: market structure, space governance, and environmental value, which then produces large-scale and multi-level spill-over effects.

(1) The carbon reduction effect of charging pile network is not mainly due to its size, but rather because it is supported by a system synergy. This study shows that the main cause for urban carbon reduction through charging pile networks has changed from simply expanding the number of charging piles at the beginning stage to creating a system where different parts work together well and are closely connected in three areas: market structure, spatial governance, and environmental value. The emission reduction benefits of isolated, separate charging station are often limited. Charging pile networks can only fully release their multiplied carbon reduction spillover effects after being integrated into a diverse and interactive market ecosystem that is compatible with fair and effective spatial layout and deeply interacting with clean energy systems.

(2) The diversification of market structures promotes technology integration, which makes it possible for charging piles to move away from individual point operations towards building ecosystems, and this is the key driver for realizing value spillover. Market players change from just a few people doing things alone to lots of different groups working together, such as big companies run by the government, small businesses owned by individuals, and organizations. This sort of team effort creates fresh methods for getting things done, such as combining solar panels (PV) that keep energy with spots where cars can get their charge from, and having cars share some of their electricity back to the power system (V2G). And it moves technology and business models forward as well, because everyone is competing and cooperating at the same time. It reduces the hidden costs and barriers associated with reducing carbon emissions due to the act of giving out energy.

(3) Spatial governance moves from "efficiency first" to "equity and efficiency balance", which is important for making sure it works well. The spatial arrangement of charging pile networks affects a city's environmental advantages. Optimize this arrangement and construct a charging network that encompasses both urban and rural regions, accurately aligning with the demands, thus guaranteeing the fairness of green mobility and the efficiency of energy conservation and emission reduction on the part of the transportation demand.

(4) The environmental value has changed from just supplying electricity to a whole system including charging. The paper indicates that people's perception of environmental benefits has been improved from simply "oil to electricity" to the deep integration of charging piles with distributed photovoltaics, energy storage, and the power grid. Charging networks could cooperate with the grid to take in variable renewable energy sources such as wind and solar power. They turn the transportation system into something that takes away energy problems instead of making them, so it helps the environment by working better with everything together than just cutting down on pollution from changing oil for electricity. Quantitatively, our case studies demonstrate that Shenzhen's integrated approach achieves approximately 0.78 kg CO_2 reduction per kWh of clean electricity generated, while the Gaoqiao Community pilot alone reduces 420 tons of CO_2 annually through 536 kWp photovoltaic integration. These figures illustrate that environmental value realization depends on technical system integration rather than simple infrastructure expansion.

5.2. Policy Recommendations

With the urgent situation of global sustainable development as the background, the construction of green infrastructure has become an important way to achieve coordinated development of economy, society and ecology. Based on the above conclusions, this paper puts forward the following three policy suggestions to improve the energy saving and emission reduction effect of charging pile network:

(1) In terms of market structure, drawing on Shenzhen's demonstration of 760+ V2G stations achieving 88,000 kWh grid interaction, the government should introduce policies that promote cross-industry cooperation between charging station operators, new energy vehicle companies, energy companies, and the State Grid, forming a "charging + industry" system together. Give extra construction aid or tax breaks to businesses that put money into all-in-one PV-storage-charging stations or join V2G test programs. Specifically, replace the current capacity-based subsidy with performance-based incentives: 15% tariff premium for stations achieving >50% renewable share, referencing Shenzhen's 80% clean energy benchmark, and 0.3 RMB/kWh capacity payment for V2G services. Change from giving out construction grants depending on how many charging points there are to rewarding charging stations which have a "clean electricity share" over 50% according to the real carbon cuts they make, so as to directly motivate operators to buy green power.

(2) Based on the identified 'coverage gradient'—county-level 97.08% vs. village-level 18%—implement a "precision gap-filling" plan for the spatial layout. Local governments need to work together with the grid company, by using electricity big data to make "charging demand heat maps" and "service gap maps". Accurately pinpoint areas lacking charging facilities, defined as regions with >50 EV ownership but <20% charging coverage, including old residential areas, outskirts of cities, small towns, countryside, and plateaus. Target 60% of the construction subsidies of public charging facilities to those places which have the most marginal benefit, ensuring <5 km detour distance in rural areas, so as to achieve a balance of fairness and efficiency. This makes sure that the advantages of the project go to all citizens and helps the growth of green movement.

(3) At the environmental value level, learning from Gaoqiao Community's 420 tons annual reduction through 536 kWp PV integration, foster green electricity synergy and make carbon resources more inclusive. Suitable areas should be required to install minimum 20% photovoltaic and 10% storage capacity along with the construction of new public charging stations >1 MW. At the same time, carry out and improve the time-of-use electricity price policy, especially to widen the peak-valley price difference to 4:1. Use economic leverage to effectively guide people to charge at times when there is plenty of renewable energy available, such as midday when the sun is shining brightly. Encourage the government to carry out carbon resource inclusive activities, allowing V2G participants to trade carbon credits in regional markets, referencing Shenzhen's 88,000 kWh interaction volume so that residents can voluntarily integrate energy saving and emission reduction into their daily lives.

Author Contributions

R.L.: conceptualization, wringing—original draft, data curation, formal analysis, formal analysis, validation, visualization; J.R.-S.: writing—review & editing, validation; Y.T.: data curation, methodology, software, writing—review & editing, project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this paper, the authors used AI to assist in article writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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