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Posted Date: 18 May 2026

doi: 10.20944/preprints202605.1155.v1

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Decision-Making on the Equalization of Urban Electric Vehicle Charging Service Layout Based on the Spatial Supply and Demand Equilibrium Principle – A Case Study of the Main Urban Area in Wuhan

Xifan Chen [1], Li Zhang [2] and Xu Tang [2,*]

[1] School of Resources and Environmental Science, Hubei University, Wuhan, China
[2] School of Resources and Environmental Sciences, Wuhan University, Wuhan, China
* Correspondence: landsky@whu.edu.cn

Abstract

This study aims to develop decision-making methods for equalizing urban electric vehicle (EV) charging services and apply them to the improvement of Wuhan's charging infrastructure. Using grid units as the basic analytical units, the study constructs measurement models for two scenarios—daily commuting and weekend travel—including a spatial demand index based on classified population-distribution prediction, a spatial supply index derived from regional charging-facility statistics, and a supply–demand balance index. Grading systems are established for single-scenario demand, layout thresholds, and supply, together with an integrated classification combining both scenarios. According to the suitability of grid units for service improvement, three optimization strategies are proposed: adding charging stations, expanding existing stations, and converting parking lots. Evaluation methods using residential quarters and commercial/service POIs are designed to assess spatial equilibrium pre- and post-optimization. An empirical study of Wuhan's main urban area shows that service satisfaction reaches 88.68% for residential quarters and 75.93% for commercial/service POIs under current conditions. The proposed scheme recommends 8 new stations, 31 station expansions, and 114 parking-lot conversions, increasing satisfaction to 99.24% and 92.35%, respectively. The model provides a feasible technical framework for urban EV charging-station planning.

Keywords: charging station; service facilities; spatial layout; supply-demand balance; optimization decision-making

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1. Introduction

Electric vehicle charging stations, which provide charging and battery swap services for electric vehicles (EVs), serve as critical infrastructure enabling the integration of urban green transportation and smart energy systems [1]. In recent years, although China has developed the world's largest, most extensive, and most comprehensive charging infrastructure network [2], mismatches with future strategic demands and development trends have exposed persistent issues, including suboptimal spatial layout, irrational structural configuration, uneven spatial distribution of services, and non-standard operational management [3]. Accelerating the optimization and expansion of charging infrastructure is crucial to strengthening charging service capacity and user satisfaction, stimulating the market potential of new energy vehicles (NEVs) [4], and facilitating the comprehensive green transition of economic and social development [5].

Existing academic research, grounded in a systems thinking approach [8] that centered on supply-demand coupling [6,7], has broadly covered the full life cycle of charging infrastructure planning and construction. Relevant research spans multiple core dimensions, including spatial accessibility statistics [9], service equity assessment [10], service demand prediction [11], and layout optimization and site selection [12]. Specifically, research on charging service demand prediction encompasses three main categories: spatial statistical analysis correlated with population distribution [13], residential quarters[14], *points of interest* (POIs) [15], transportation networks [16], and traffic flow [17]; Monte Carlo simulations based on trip chain theory [18]; and fuzzy inference models that account for heterogeneity in user charging behavior [19]. Research on the supply side of charging services mainly focuses on path analysis within a defined service radius [20] and the delimitation of charging station service scopes using weighted Voronoi diagrams [21]. Taking supply-demand balance as a starting point, mainstream decision-making approaches for charging station layout optimization analyze the spatial characteristics of supply-demand clusters, including overlapping service ranges, excessive service distances, and coverage gaps [22,23]. Such approaches are designed to minimize spatial layout costs [24] and maximize service efficiency [25], while considering comprehensive constraints including distribution network capacity [26], multi-facility synergy [27], and land use compatibility [28], with research priorities typically concentrated on facility location, capacity configuration [29], and comprehensive benefit assessment [30]. Overall, although existing research on charging facility layout has formed a relatively complete research framework, there remains an urgent need to refine targeted methodologies and systematic techniques that can support the full decision-making process of charging service layout optimization.

As the largest metropolis in Central China and a national pilot city for the promotion and application of NEVs, Wuhan has carried out extensive and pioneering explorations in multiple key areas, including branded market access for charging stations [31], intelligent and low-carbon facility development [32], high-efficiency charging mode innovation [33], and operational service quality improvement [34]. However, existing studies have several limitations. Some are limited to specific districts, such as Zhuankou [35], Hongshan [36], Wuchang [37], and Hankou [38]. Others have explored citywide spatial distribution characteristics [39,40], supply-demand matching status [41], and multi-network integrated planning [42,43], yet remain insufficient to fully support the city’s current development goals. These goals include the construction of a high-quality charging infrastructure system [44] and the realization of a "three-year doubling" target of EV charging service capacity [45]. Therefore, integrating relevant methods in this field to conduct a systematic analysis and diagnosis of the spatial layout of EV charging stations in Wuhan is of great practical significance for improving the city’s charging infrastructure system, establishing green residential living circles, and promoting high-quality urban renewal.

2. Methodologies

Following the basic logic of spatial supply-demand coupling, this section defines the system components and main demand scenarios for urban EV charging services. On this basis, it constructs an indicator system and methodological models for measuring the supply-demand balance of charging services, and designs a technical framework for evaluation and decision-making to support the optimization of charging station layout.

2.1. System Elements for Charging Station Layout Evaluation

The urban EV charging station layout system consists of three core parts: charging service supply, charging service demand, and the spatial matching between supply and demand. The components, characteristics, and relationships of each part are elaborated as follows.

(1) Charging Service Demand Objects

Battery electric vehicles (BEVs) and *plug-in hybrid electric vehicles* (PHEVs), which rely on external charging to convert electrical energy into chemical energy stored in on-board batteries for vehicle propulsion and power supply, form the basic demand entities of urban EV charging services. EVs can be divided into four categories based on ownership and usage scenarios, private EVs, electric taxis, electric buses, and other specialized EVs. The specific features of each category are as follows:

1) Private EVs are primarily used for daily commuting or weekend travel by individuals or families, and are typically charged in residential areas or near workplaces; 2) Electric taxis cover ride-hailing or metered taxis providing personalized passenger transport services. The majority are operated by professional companies or mobility platforms (e.g., T3, Didi), and are centrally charged at public charging stations or battery swap stations; 3) Electric buses are medium and large passenger vehicles operating on fixed routes and scheduled timetables, and are generally charged at bus depots or route terminals; 4) Other specialized EVs include official government-use vehicles, freight trucks, and other types, which are typically charged at designated spots in institutional parking lots or specific areas. Among all NEVs, private EVs account for the vast majority (approximately 493,170, accounting for 85% of the 580,200 total EVs in Wuhan by 2025) and are the core driver of growth in NEV consumption. Accordingly, the planning and layout of corresponding charging service facilities have become a key priority in urban infrastructure development, which also delimits the research scope of this study.

(2) Charging Service Supply Facilities

EV charging is enabled by core service facilities including charging piles, charging stations, and supporting management systems. As the fundamental infrastructure unit, charging piles are installed in public parking lots, residential quarters, commercial buildings, transportation hubs, and other locations to provide convenient charging services. These piles fall into two types: DC fast chargers and AC slow chargers. Charging stations are integrated service sites equipped with clusters of charging piles, along with ancillary facilities such as rest areas and retail outlets. The construction and operation of these facilities face certain economic and technical barriers, as they depend on safe, reliable, and compatible power, electronic, and communication technologies, as well as a dedicated management system for equipment status monitoring, charging order management, billing settlement, and user services. Furthermore, NIMBY (*Not in My Backyard*) effects triggered by charging safety risks result in a discrete, point-like spatial distribution of such facilities. The number of charging piles deployed at a station affects the number of vehicles that can be charged simultaneously, while the power rating of the piles directly affects charging time. Therefore, the service capacity of a charging station (Es) is defined as the maximum number of vehicles that can be effectively served within a specified time period. A station is deemed overloaded when charging demand exceeds its capacity, and under-loaded or adequately loaded when demand is at or below capacity.

(3) Charging Service Scenario Relationships

In line with the cyclical driving patterns of private car owners (weekday commuting, weekend entertainment/shopping trips), EV charging demand can be divided into two scenarios with distinct spatial supply-demand relationships: daily commuting and weekend travel. 1) Daily commuting scenario: Owners typically charge at charging stations located in or near their residential areas (within a radius D_1). At any spatial unit u_i, the charging service demand index c_i is proportional to the fixed population within its neighborhood, while the corresponding service supply index s_{ci} is calculated based on the total charging service capacity within the same area. 2) Weekend travel scenario: Owners tend to charge at stations adjacent to POI clusters within commercial centers (within a radius D_2). At any spatial unit u_i, the charging service demand index t_i is calculated based on the population attracted by the commercial center, which is allocated to the POIs within the neighborhood. The corresponding service supply index s_{ti} is calculated based on the total charging service capacity within the same area.

Theoretically, EV owners will prioritize the nearest available facility, forming a complete spatial duality relationship "Facility f_i- Domain $E_{1\text{-}i}$" as shown in Figure 1(a). When planning requires spatial point u_i to access charging services within a specified ideal distance (D_1 or D_2), an incomplete duality relationship "Facility F_i- Domain $E_{2\text{-}i}$" is formed, as shown in Figure 1(b). The goal of charging service layout optimization is to eliminate or minimize the service blind spots under planning constraints, and to achieve an overall balance between supply and demand across the entire urban area.

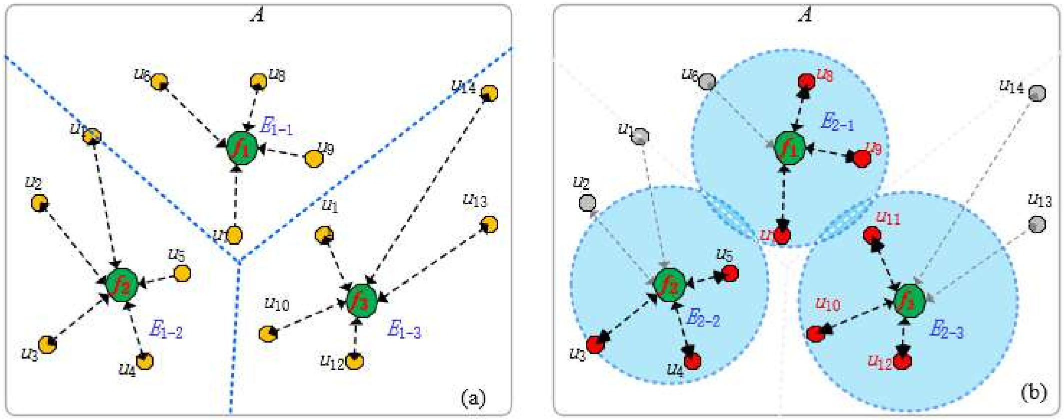


Figure 1. Spatial mapping of the supply and demand relationship of charging services under current conditions and planning constraints.

2.2. Model for Measuring Charging Service Equity

Corresponding to the components of the urban EV charging station layout system, indicator measurement models for spatial demand, spatial supply, and supply-demand balance are constructed sequentially.

(1) Spatial Demand Index for Charging Services

For the daily commuting scenario, a demand circle of area s_i is defined with any spatial unit u_i as the center and a radius D_1 (set to 3 km, referencing the standard of the urban residential living circle). The residential population density w_i within the demand circle is then statistically calculated. The charging service demand index c_i is calculated by weighting the city's per capita private EV ownership E_p and average charging frequency E_f, with the model specified as follows:

$$c_i=(s_i\times w_i)\times E_p\times E_f\times 5/7 \qquad (1)$$

For the weekend travel scenario, a demand circle of area s_i is defined with any spatial unit u_i as the center and a radius D_2 (set to 0.5 km). For the *POIs* (count n_i) within the demand circle that belong to a center of grade k (among m grades), the service area s_j, population density w_j, and resident travel probability r_j of the center across grades (k, k+1, ..., m) are statistically determined. The total travel population probabilistically attracted by the center is calculated and equally apportioned to the center's POIs (center POI count n_b). The charging service demand index t_i is subsequently calculated by weighting the apportioned population per POI within the demand circle with E_p and E_f, with the model specified as follows:

$$t_i=\sum_{j=k}^{m}\left(s_j\times w_j\times r_j\right)\times\frac{n_i}{n_b}\times E_p\times E_f\times 2/7 \qquad (2)$$

(2) Spatial Supply Index for Charging Services

With spatial unit u_i as the center, the following parameters within the corresponding demand circle (radius D_1) are statistically calculated: the number of charging stations n_i, the number of charging piles m_j in each station, the average daily service capacity per pile E_s, and the distance d_j between the station and point u_i. The spatial supply index s_{ci} for the daily commuting scenario is calculated via weighted summation as:

$$s_{ci}=\sum_{j=1}^{n_i}[m_j\times E_s\times(1-\frac{d_j}{D_1})] \qquad (3)$$

With spatial point u_i as the center, the same parameters within its demand circle (radius D_2) are statistically calculated, and the spatial supply index s_{ti} for the weekend travel scenario is calculated as:

$$s_{ti}=\sum_{j=1}^{n_i}[m_j\times E_s\times(1-\frac{d_j}{D_2})] \qquad (4)$$

(3) Supply-demand Balance Index for Charging Services

For any spatial point s_{ti}, the supply-demand balance indices h_{i1} and h_{i2} for the two scenarios are calculated as the ratio of the supply indices (s_{ci}, s_{ti}) to demand indices (c_i, t_i), respectively：

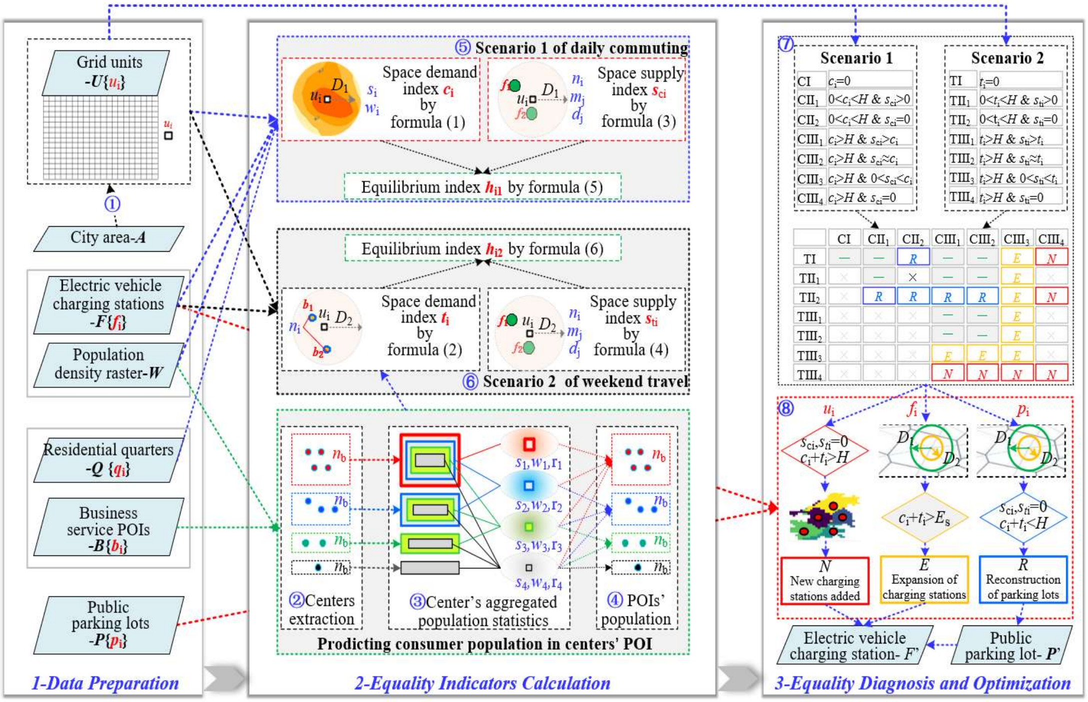
$$h_{i1}=s_{ci}/c_i \qquad c_i\neq 0 \qquad (5)$$

$$h_{i2}=s_{ti}/t_i \qquad t_i\neq 0 \qquad (6)$$

Appropriate "Supply-demand ratio" standards are determined for each scenario. Spatial points u_i are classified based on h_i into three balance levels: ① Supply > Demand, ② Supply ≈ Demand, ③ Supply < Demand. The proportion of units at each balance level within the study urban area A, as well as their changes before and after optimization, are used as the core criteria for evaluating the current layout status and the effectiveness of optimization measures.

2.3. Technical Process for Charging Station Layout Evaluation

Based on the above analysis, the evaluation of urban charging station layout adopts the following methodological approach: "Taking grid units as the basic evaluation unit, calculate the spatial demand index, spatial supply index, and supply-demand balance index for charging services under the two scenarios; taking residential quarters and commercial/service POIs as diagnostic units, overlay them with grid units to classify supply-demand balance levels, and propose targeted optimization strategies for supply-demand matching." The technical evaluation process is shown in Figure 2.



Scenario 1	
CI	$c_i=0$
CII$_1$	$0<c_i<H$ & $s_{ci}>0$
CII$_2$	$0<c_i<H$ & $s_{ci}=0$
CIII$_1$	$c_i>H$ & $s_{ci}>c_i$
CIII$_2$	$c_i>H$ & $s_{ci}\approx c_i$
CIII$_3$	$c_i>H$ & $0<s_{ci}<c_i$
CIII$_4$	$c_i>H$ & $s_{ci}=0$

Scenario 2	
TI	$t_i=0$
TII$_1$	$0<t_i<H$ & $s_{ti}>0$
TII$_2$	$0<t_i<H$ & $s_{ti}=0$
TIII$_1$	$t_i>H$ & $s_{ti}>t_i$
TIII$_2$	$t_i>H$ & $s_{ti}\approx t_i$
TIII$_3$	$t_i>H$ & $0<s_{ti}<t_i$
TIII$_4$	$t_i>H$ & $s_{ti}=0$

	CI	CII$_1$	CII$_2$	CIII$_1$	CIII$_2$	CIII$_3$	CIII$_4$
TI	—	—	R	—	—	E	N
TII$_1$	×	—	×	—	—	E	×
TII$_2$	×	R	R	R	R	E	N
TIII$_1$	×	×	×	—	—	E	×
TIII$_2$	×	×	×	—	—	E	×
TIII$_3$	×	×	×	E	E	E	×
TIII$_4$	×	×	×	N	N	N	N

Figure 2. Technical processes for evaluation and decision-making of equalization of electric vehicle charging station layout.

Description of the technical process: ① Basic grid unit generation: With the urban boundary study area A as the scope, a 100 m × 100 m grid of points is created via ArcGIS's fishnet tool. Water bodies are then clipped out from the grid, resulting in grid layer U. ② Clustering and grading of commercial centers: Commercial POIs within the study urban area are extracted. Spatial clustering is performed using a local density gradients-based Python algorithm to identify Grade I, II, III, and IV commercial centers, and the POI set for each center is determined. ③ Prediction of weekend population clustering within commercial centers: In accordance with the principle that higher-grade centers encompass the functions of lower-grade ones, the functional levels of centers are defined. Residents' daily weekend travel probabilities (r_1,r_2,r_3,r_4) are assigned corresponding to each functional level. Service areas for centers are defined using the Voronoi tool. Population density raster data are overlaid to calculate the probabilistically attracted travel population (w_1,w_2,w_3,w_4) for each center. ④

Apportionment of attracted population to POIs within commercial centers: The total population aggregated at each commercial center is apportioned to each POI unit within its cluster, to obtain the service population size corresponding to each POI in the center. ⑤ Calculation of demand and supply indices for the daily commuting scenario: Demand circles are constructed with a radius D_1, and the demand index c_i for each grid unit is calculated based on population density using Formula (1). Combined with the spatial distribution of charging stations, the supply index s_{ci} is calculated using Formula (3). ⑥ Calculation of demand and supply indices for the weekend travel scenario: Demand circles are constructed with a radius D_2. and the demand index t_i for each grid unit is calculated based on the distribution of commercial center POIs and their attracted population according to Formula (2). Combined with the spatial distribution data of charging facilities, the supply index s_{ti} is calculated using Formula (4). ⑦ Classification of supply-demand balance levels: Using Formulas (5) and (6), the balance indices h_{i1} and h_{i2} for the two scenarios are calculated. Grid units are then classified into 7 balance levels based on the coupling relationships between demand and supply indicators: Type I (Demand Deficient), Type II_1 (Supply Response under Low Demand), Type II_2 (Supply Deficient under Low Demand), Type III_1 (Sufficient Supply under High Demand), Type III_2 (Supply-demand Matched under High Demand), Type III_3 (Insufficient Supply under High Demand), Type III_4 (Supply Deficient under High Demand). ⑧ Formulation of differentiated optimization strategies: Based on the combination of balance levels across the two scenarios, grid units of different types are extracted. In conjunction with constraints of facility types (charging stations F and parking lots P) and service capacity, three optimization strategies are developed: 1) For Type N units (High Demand, Supply Deficient), new charging stations are required. Based on the clustering intensity of short-distance travel demand, units with $t_i>H$ are clustered with a radius D_2 to identify the central points for new stations; for units with ti $<H$, site selection is conducted with a radius D_1. 2) For Type E units (High Demand, Insufficient Supply), expansion of existing charging stations is required. Voronoi diagrams are drawn for existing charging stations, and clipped by the service circles for daily commuting (D_1) and weekend travel (D_2). Demand indices c_i and t_i are corrected based on the ratio of the Thiessen polygon area to service circle area. The comprehensive load for both scenarios is calculated, with the spatial load index defined as $C_1=(c_i+t_i)/(22*5)$. A station is deemed overloaded and in need of expansion if $C_1>1$. 3) For Type R units (Low Demand, Supply Deficient), conversion of existing parking lots for charging deployment is required. Voronoi graphs are generated for existing parking lots. Demand indices are similarly corrected, and the comprehensive demand load is calculated. For units with $c_i+t_i<H$, the spatial load index for parking lots $C_2=(c_i+t_i)/5$ is calculated to determine the scale of conversion. ⑨ Evaluation of decision scheme effectiveness: Taking residential quarters and commercial POIs as evaluation units, the proportional changes in the supply-demand balance levels of these units before and after optimization are compared, to assess the improvement in charging service equality achieved by the proposed decision-making scheme.

3. Case Study

3.1. Urban Location and Study Area

The main urban area of Wuhan, covering 955.15 square kilometers, is selected as the study area. This area includes seven administrative districts: Jiang'an, Jianghan, Qiaokou, Hanyang, Wuchang, Qingshan, and Hongshan. The distribution of the area is illustrated in Figure 3.

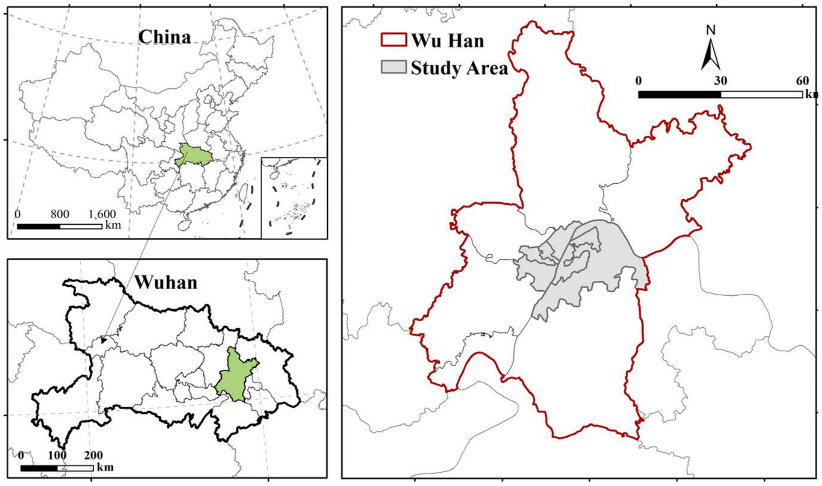


Figure 3. Geographical location and the main urban area of Wuhan City.

3.2. Data Collection and Organization

3.2.1. Parameter Data Collection

Model parameter data relevant to evaluating the charging station layout system in Wuhan were obtained or derived from the Wuhan Statistical Yearbook, as well as official bulletins issued by local departments of Natural Resources, Urban Construction, and Traffic Management. The sorted and compiled parameter data are shown in Table 1.

Table 1. Parameters for EV charging station layout planning in Wuhan.

Parameter Name	Data Source	Value/Calculation
Total permanent urban population	Wuhan Statistical Bulletin	13.8091 million
Total number of electric vehicles (EVs)	Wuhan Traffic Management Bureau	580,200 vehicles
Proportion of private EVs	Wuhan Traffic Management Bureau	85%
E_p Per capita private EV ownership	Private EV count / Total permanent resident population	0.0357
Average range of private EVs	China Automobile Dealers Association (CADA)	350 km
Average daily mileage of private EVs		50 km
E_f Average charging frequency		0.14 times/day
Total public charging piles in Hubei Province	Average range / Average daily mileage	170000
Ratio of slow/fast charging piles	China Electric Vehicle Charging Infrastructure Promotion Alliance (as of Jan 2025)	65.88%/34.12%
Total public charging stations in Hubei Province		7,524 stations
Average number of piles per charging station	Total piles / Total stations	22 piles
Average charging duration per pile	(Fast ratio*fast Average time 0.76h) + (Slow ratio slow Average time 7h)	4.87 hours
Average daily service capacity per pile	24 hours / Average charging duration	5 vehicles/day
E_s Average daily service capacity per station	Average piles per station*Average daily capacity per pile	22*5 vehicles/day
H Threshold demand index for layout	E_s×80%	88 vehicles/day

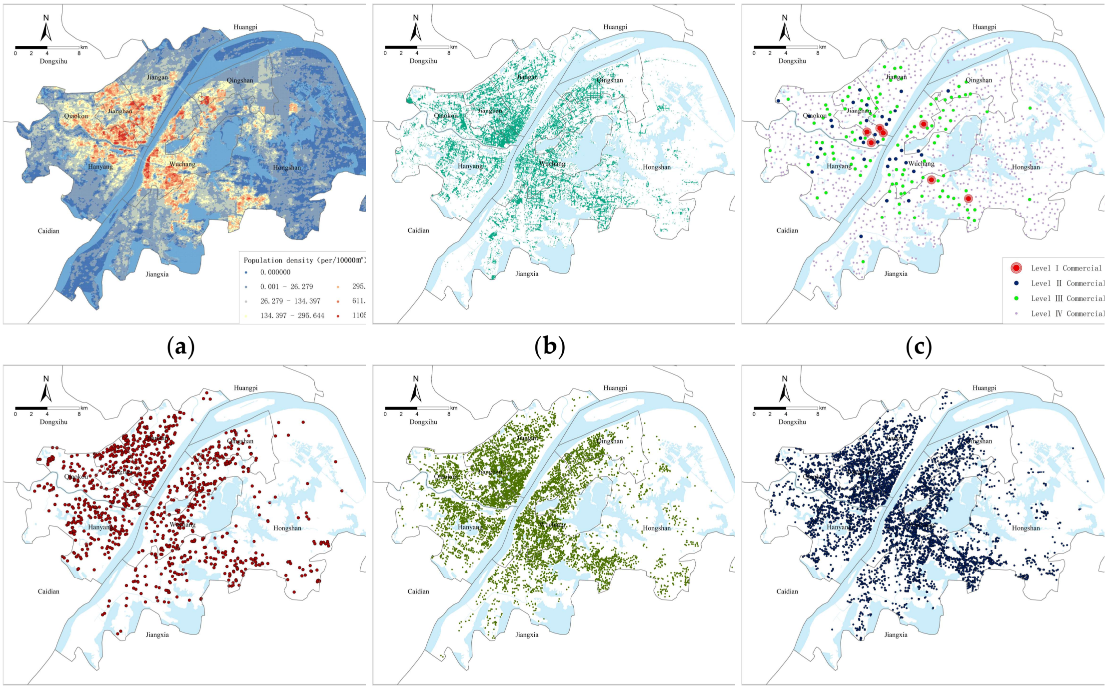
3.2.2. Spatial Data Collection

Spatial data for the evaluation of Wuhan's charging station layout system were obtained from natural resources management departments, Gaode Map, and Baidu Map. All spatial data were standardized, coded, and imported into ArcGIS to construct corresponding feature layers. Attribute fields were designed in accordance with the evaluation technical process detailed in Section 2.3, followed by data verification and cleaning. The specific sources of all data are listed in Table 2：

Table 2. Spatial data for decision-making of charging station layout in Wuhan.

System Element	Data Source	Data Specification	Format
A: City area	Wuhan Natural Resources and Planning Bureau, 2024 Grading Results	7 districts	SHP
U: Grid units	100 m × 100 m grid units generated from city area A	75,592 units	SHP
W: Population density raster	WorldPop / Baidu Maps (2025 population heatmap, 100 m resolution)	95,516 points	TIF
B: Business service POIs	Gaode Map / Baidu Maps (Web collection, Jan 2025)	199,648 points	SHP
D: Commercial centers	Clustering of commercial POIs B/ 2024 Grading Results	948 centers	SHP
F: EV charging stations	Gaode Map / Baidu Maps (Jan 2025)	1,226 stations	SHP
Q: Residential quarters	Gaode Map / Baidu Maps (Jan 2025)	8,182 points	SHP
P: Public parking lots	Gaode Map / Baidu Maps (Jan 2025)	5,928 points	SHP

The spatial distribution of the processed layers (W: population density raster, B: commercial POI points, D: commercial centers, F: EV charging stations, Q: residential quarters, P: public parking lots) are shown in Figures 4(a) to 4(f).



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 4. Spatial distribution of basic elements for layout decision analysis of charging stations in Wuhan: (**a**) population density raster, (**b**) commercial POI points, (**c**) commercial centers, (**d**) EV charging stations, (**e**) residential quarters and (**f**) public parking lots.

doi:10.20944/preprints202605.1155.v1

3.3. Calculation of Evaluation Indicators and Results

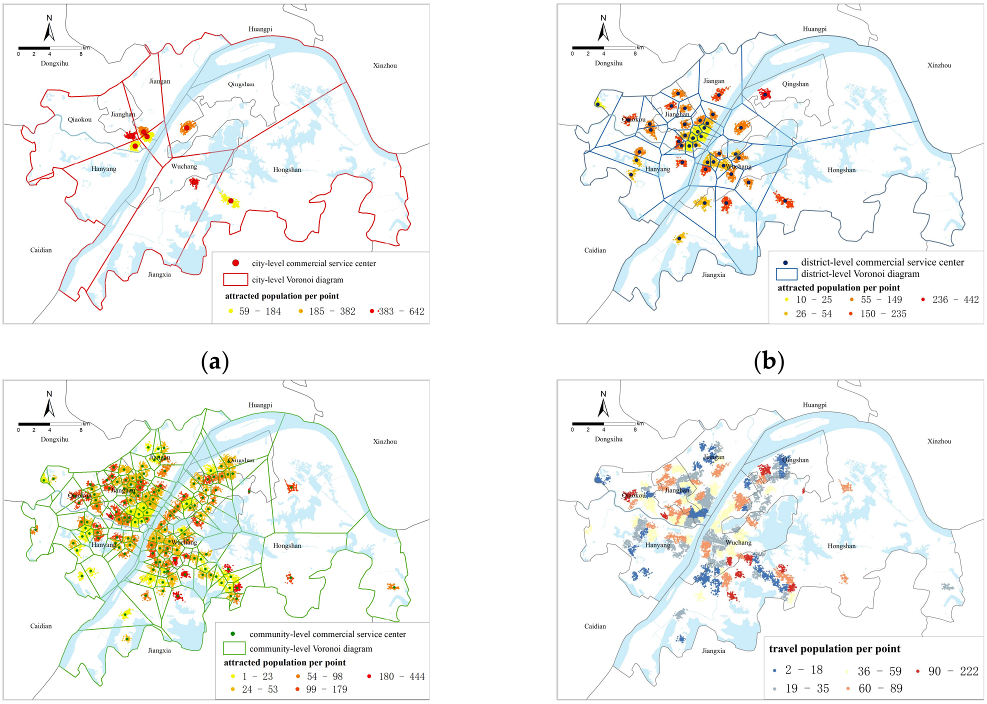
3.3.1. Prediction of Travel Population Distribution

Following Steps ②–④ of the procedure described in Section 2.3, a total of 948 commercial centers were identified based on the scale characteristics of commercial POIs (7 Grade I, 33 Grade II, 109 Grade III, 799 Grade IV). Key indicators and parameters for each grade such as service function, number of POIs, radius of influence (m), travel frequency, and weekend travel probability were shown in Table 3.

Table 3. Indicators and parameters for the classification function of the commercial service center in Wuhan.

Function Type	**Dependent Center Grade**	**Number of Centers**	**Number of POIs**	**Radius of Influence**	**Travel Frequency f_i (times/day)**	**Weekend Travel Probability r_i（$=f_i$*7/2）**
City level	Grade I	7	26148	22550	1/28	1/8
District level	Grades I, II	40	78216	22550	1/14	1/4
Community level	Grades I, II, III	149	143821	10370	1/7	1/2
Neighborhood level	Grades I, II, III, IV	948	199648	2700	1	0

The service radius of the neighborhood level functions of commercial centers is less than 3 km; although residents have a relatively high travel probability to such centers, walking is their dominant travel mode. Accordingly, for the weekend travel scenario, the demand for charging services is statistically calculated and predicted based on the population attracted by city level, district level, and community level commercial centers. The service areas of city level, district level, and community level commercial centers delineated by Voronoi graphs, overlaid with the population density raster data, were illustrated in Figure 5.



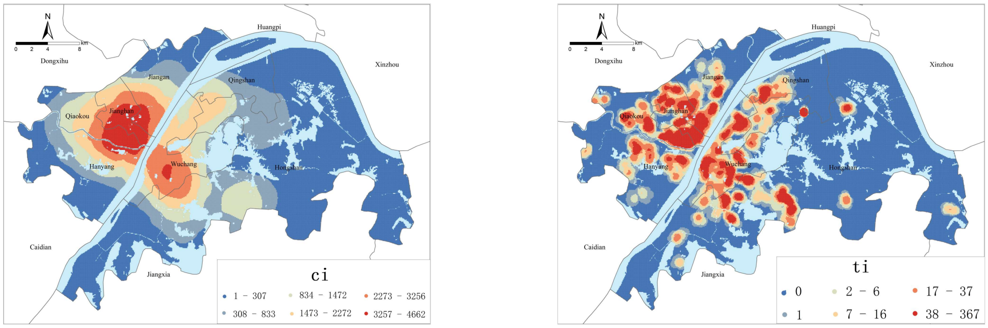
(**a**) (**b**)

(**c**) (**d**)

Figure 5. Service areas of three levels functional (**a**, **b**, **c**) and predicted gathering populations per day of weekend (**d**) in commercial centers in Wuhan.

3.3.2. Spatial Demand Statistics for Charging Services

Following Step ⑤,⑥ of the procedure described in Section 2.3, the spatial demand indices c_i (daily commuting) and t_i (weekend travel) were calculated for each grid unit. The spatial distribution of calculation results was presented in Figure 6(a) and Figure 6(b).



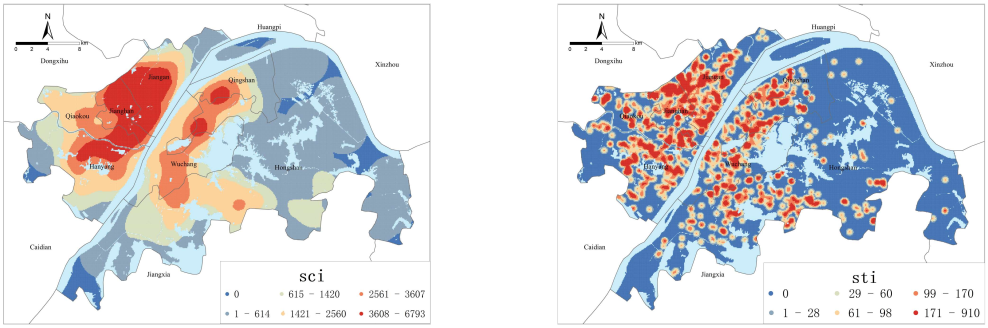
(**a**) (**b**)

Figure 6. Distribution maps of charging service demand indices c_i (**a**) and t_i (**b**) in Wuhan.

The demand coverage rates of charging services for grid units under the daily commuting and weekend travel scenarios were 100% and 32.32%, respectively.

3.3.3. Spatial Demand Statistics for Charging Services

Following Step ⑤,⑥ of the procedure described in Section 2.3, the spatial supply indices s_{ci} (daily commuting) and s_{ti} (weekend travel) were calculated for each grid unit. The spatial distribution of calculation results was illustrated in Figure 7(a) and Figure 7(b).



(**a**) (**b**)

Figure 7. Distribution maps of charging service supply indices s_{ci} (**a**) and s_{ti} (**b**) in Wuhan.

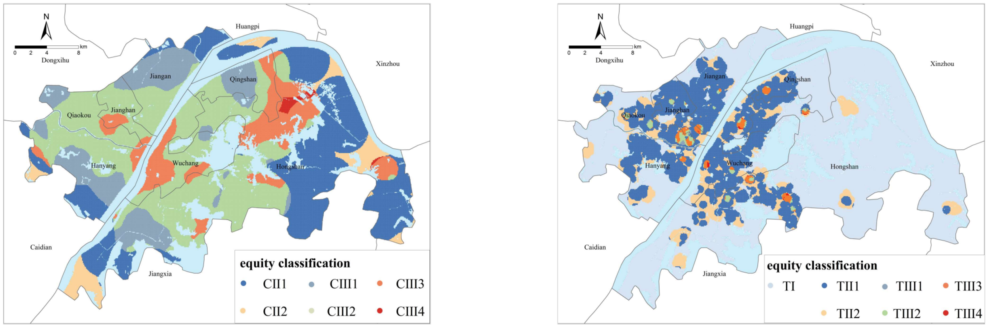
The supply coverage proportions of charging services for grid units in the daily commuting and weekend travel scenarios were 92.643% and 34.851%, respectively.

3.3.4. Supply-Demand Balance Statistics for Charging Services

Following Step ⑦ of the procedure described in Section 2.3, the balance indices h_{i1} (daily commuting) and h_{i2} (weekend travel) were calculated for each grid unit, followed by equity-based classification. The interval ranges of the balance indices and the proportion of grid units in each category were listed in Table 4, with corresponding spatial distributions in Figure 8(a) and Figure 8(b).

Table 4. Equity classifications by charging service supply and demand of two scenarios in Wuhan.

Daily Commuting Scenario				Weekend Travel Scenario			
Class	**Supply-demand Condition**	h_{i1}	**Proportion (%)**	**Class**	**Supply-demand Condition**	h_{i2}	**Proportion (%)**
CⅠ	$c_i=0$	null	0%	TⅠ	$t_i=0$	null	62.90%
CⅡ$_1$	$0<c_i<H$ & $s_{ci}>0$	—	28.74%	TⅡ$_1$	$0<t_i<H$ & $s_{ti}>0$	—	26.48%
CⅡ$_2$	$0<c_i<H$ & $s_{ci}=0$	0	4.86%	TⅡ$_2$	$0<t_i<H$ & $s_{ti}=0$	0	8.65%
CⅢ$_1$	$c_i>H$ & $s_{ci}>c_i$	3-5	15.50%	TⅢ$_1$	$t_i>H$ & $s_{ti}>t_i$	3-5	0.09%
CⅢ$_2$	$c_i>H$ & $s_{ci}\approx c_i$	1-3	38.13%	TⅢ$_2$	$t_i>H$ & $s_{ti}\approx t_i$	1-3	0.78%
CⅢ$_3$	$c_i>H$ & $0<s_{ci}<c_i$	0-1	12.21%	TⅢ$_3$	$t_i>H$ & $0<s_{ti}<t_i$	0-1	1.04%
CⅢ$_4$	$c_i>H$ & $s_{ci}=0$	0	0.56%	TⅢ$_4$	$t_i>H$ & $s_{ti}=0$	0	0.07%

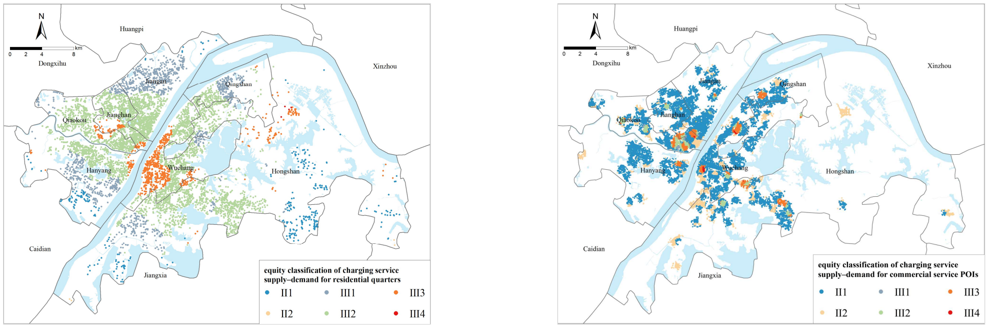


(**a**) (**b**)

Figure 8. Distribution maps for grid units' equity classification by charging service supply and demand of two scenarios in Wuhan: (**a**) daily commuting; (**b**) weekend travel.

3.3.5. Statistics for Evaluation Units

Following Step ⑦ of the procedure described in Section 2.3, the grid unit calculation results were overlaid to derive the supply-demand balance classification indices for residential quarters (daily commuting scenario) and commercial center POIs (weekend travel scenario). The spatial distribution of the classification results was shown in Figure 9(a) and Figure 9(b).



(**a**) (**b**)

Figure 9. Distribution maps for equity classification of residential quarters (**a**) and commercial center POIs (**b**) by charging service supply and demand in Wuhan.

Under the daily commuting scenario, the demand coverage rate and supply coverage rate of residential quarters reached 100% and 99.9%, respectively. The proportions of residential quarters where supply > demand, supply ≈ demand, and supply < demand were 17.21%, 71.47%, and 11.32%, respectively. Under the weekend travel scenario, the corresponding indicators for commercial POIs were 100%, 89.87% and 1.10%, 74.83%, 24.07%, respectively. The comprehensive guarantee rate for regional charging services reached 85.04%.

3.4. Diagnostic Analysis and Optimization Decision

3.4.1. Formulation of Charging Service Layout Optimization Scheme

Following Step ⑧ of the procedure described in Section 2.3, a spatial layout optimization scheme for EV charging services in Wuhan was formulated by integrating the supply-demand classification results and grid unit types. Three targeted optimization strategies were adopted in the scheme (*N*: new station addition, *E*: station expansion, *R*: parking lot conversion), with specific implementation details as follows: *N*: Add new charging stations at locations including 3 in Wuchang District and 5 in Hongshan District; *E*: Expansion of charging stations, distributed as 1 in Jiang'an, 5 in Jianghan, 6 in Qiaokou, 3 in Hanyang, 7 in Wuchang, 2 in Qingshan, and 7 in Hongshan; *R*: Conversion of 114 parking lots, distributed as 5 in Jiang'an, 9 in Jianghan, 22 in Qiaokou, 5 in Hanyang, 19 in Wuchang, 6 in Qingshan, and 48 in Hongshan. The spatial layout of optimization results delivered by these three strategies was shown in Figure 10.

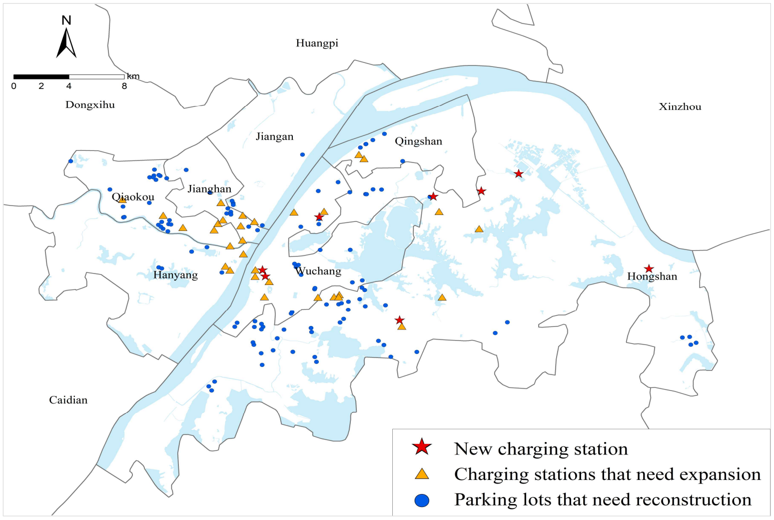


Figure 10. Distribution map of the charging service layout optimization results by three paths in Wuhan.

3.4.2. Evaluation of the Optimization Scheme

Following Step ⑨ of the procedure described in Section 2.3, a statistical analysis was conducted on the proportional changes in the equity classification of charging service supply-demand matching for evaluation units, before and after the implementation of Wuhan's optimization scheme. Scheme effectiveness was evaluated via cross-comparison of these classification proportions, with statistical data for both scenarios pre- and post-optimization presented in Table 5.

Table 5. Optimization scheme's effects on enhancing the equity of charging services supply and demand (%).

Scenario	State	I	II$_1$	II$_2$	III$_1$	III$_2$	III$_3$	III$_4$
Daily Commuting - Residential quarters	Original	0	4.45	0.05	17.21	67.02	11.22	0.05
	Optimized	0	4.50	0	17.21	77.53	0.76	0
	Change	0	+0.05	-0.05	0	+10.51	-10.56	-0.05
Weekend Travel - Commercial POIs	Original	0	64.44	9.76	1.10	10.39	13.94	0.37
	Optimized	0	70.16	4.04	1.10	21.09	3.46	0.14
	Change	0	+5.72	-5.72	0	+10.70	-10.48	-0.23

As indicated in the table, the share of evaluation units with fully met charging service demand (Types II_1, III_2) increased significantly after optimization. Specifically, the service satisfaction rate of residential quarters (measuring the daily commuting scenario) rose from 88.68% to 99.24%, while that of commercial center POIs (measuring the weekend travel scenario) climbed from 75.93% to 92.35%. This confirms the substantial improvement effect of the proposed optimization scheme.

4. Conclusions

This paper puts forward an equity-oriented decision-making method for the spatial layout of urban EV charging services, with the core objective of improving the system of NEV charging infrastructure. This method covers the entire closed-loop analytical requirements of the charging facility planning workflow, spanning six core links: "system elements — scenario classification — indicator measurement — feature identification — problem diagnosis — optimization decision". Its feasibility has been verified through empirical case analysis. The definition of spatial supply-demand relationships for charging systems under the daily commuting and weekend travel scenarios is highly consistent with the travel and charging behavioral characteristics of private EV owners. The prediction and statistical analysis of population clustering within commercial centers draw on evaluation methods from urban land grading research, laying a solid theoretical foundation for demand quantification. The analytical framework for spatial equilibrium evaluation and diagnosis, built on supply-demand matching comparison, conforms to the general evaluation logic for public service facility layout planning. The three differentiated optimization strategies proposed (new station addition, station expansion, parking lot conversion) present distinct application advantages, including spatial localizability, index traceability, and analyzable effects. This framework thus provides universally applicable technical support for the planning of urban EV charging stations.

There are still limitations to this study. Constrained by data availability, Euclidean distance is adopted for the accessibility measurement of charging services, without considering the influence of heterogeneous distribution of urban road networks. Incorporating actual path distance and conducting more refined statistical analysis of relevant parameters will be crucial in future research and practical applications.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, visualization, writing—original draft, X.C.; Validation, investigation, resources, writing—review and editing, L.Z.; Conceptualization, validation, resources, writing—review and editing, supervision, project administration, funding acquisition, X.T.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 42471454.

Data Availability Statement: Data is contained within the article or supplementary material. The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Acknowledgments: This research was funded by the State Scholarship Fund under the certificate number 42471454. So, the authors would like to thank the China Scholarship Council (CSC) for grant supports of this research. In addition, the authors would like to thank all team members for their valuable contributions to data collection and discussion. No generative AI tools were used in the preparation of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric vehicle	NIMBY	Not in my backyard
NEV	New energy vehicle	CADA	China Automobile Dealers Association
BEV	Battery electric vehicle	SHP	Shapefile
PHEV	Plug-in hybrid electric vehicle	TIF	Tagged image file format
POI	Point of interest		
DC	Direct current		
AC	Alternating current		

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