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Site Suitability Analysis for Electric Vehicle Charging Stations Using a GIS-Based Multi-Criteria Decision Model: A Case Study of Islamabad

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Abstract

Electric vehicles (EVs) are attracting choice and adoption as a travel mode in global transportation systems, driven by technological innovation, economic considerations, and advancing sustainable urban development. The planning, development, design, and location of EV charging stations are challenging tasks for underdeveloped countries such as Pakistan. To propose the site location for an EV charging station, this study comprises Multi-Criteria Decision Analysis and Geographic Information Systems. The study adopts a mixed-methods design, combining qualitative expert input with quantitative spatial analysis to investigate technical, social, and infrastructural criteria. The study considers indicators, including site suitability, population density, interaction between land use and transport, road network, transportation interactions, existing electricity grid infrastructure, and existing fueling and charging stations. This research presents pairwise expert comparisons, indicating that grid capacity (0.28) and demand (0.30) are important factors to consider. A composite suitability Index (CSI) through GIS-weighted overlay was used to classify the area into low, medium, and high suitability zones. According to the CSI, 26% of the area falls in highly suitable areas for EV infrastructure in Islamabad, and 41% falls in medium-to-high suitable areas. The remaining 33% area lies in low-suitability peripheral zones near the hilly region of Islamabad city, which is not considered suitable for EV infrastructure. A total of 67% of the city's area is suitable for EV infrastructure.

Keywords: electric vehicles; site suitability analysis; urban infrastructure planning; spatial optimization; MCDM

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1. Introduction

Electric vehicles (EVs) are attracting the attention of transportation planners as a solution to environmental issues such as climate change and air pollution, particularly in regions like Europe and China. In 2020, amid growing attention, Pakistan enacted the first National Electric Vehicle Policy (NEVP) to provide guidelines and promote EV incentives [1]. Due to policy adoption over the last five years, the state-level planning and development infrastructure for EVs is limited, leading people to be less attracted to EVs than in other countries. Global practices highlight that the significant location of EV charging stations is important for attracting EVs. A lack of properly designed and poorly located charging amenities leads to reduced consumer attraction and discourages the investment [2].

Countries where the EV infrastructure is developed and plays a significant role in ridesharing, recommend data-driven deployment models to ensure adequate accessibility, coverage, and demand fulfillment [3]. Location-optimization approaches have also been applied to public transport electrification; an optimization model for locating electric bus charging infrastructure in Stockholm [4]. In contrast, Pakistan lacks a comprehensive scientific planning model for EV charging stations, resulting in ad hoc site selection and inefficient infrastructure. This study addresses this gap by developing a GIS-based site suitability model for charging stations in Islamabad using MCDA (1). Key findings indicate that applying GIS and MCDA enables the identification of optimal locations based on both spatial and non-spatial criteria (2), guiding policymakers, urban planners, and utility providers toward efficient and sustainable deployment of EV infrastructure [5,6].

The development of EV charging infrastructure is essential for achieving carbon peak and neutrality targets [7]. The effective rollout of EVs depends on matching adoption rates with the strategic deployment of charging stations [8]. For example, according to the IEA's 2024 global report, EV adoption increased by 25%, a trend with the potential to significantly reduce CO_2 emissions by about 2 Gt [9]. This is particularly relevant in countries like Pakistan, where transport contributes heavily to urban pollution and carbon output, making rapid action and forecasting critical. Here, scientific tools like GIS for spatial analysis and MCDM for systematic evaluation help address planning challenges, particularly in regions with high dependence on conventional fuels, such as the Gulf and Middle East. Recent studies demonstrate that using GIS and MCDM helps identify optimal locations for EV charging stations, supporting targeted infrastructure investments and sustainable urban planning [10]. In fact, GIS-based analyses confirm that aligning infrastructure with EV ownership patterns enables effective, evidence-based planning for smart cities and sustained growth of the EV network [11].

Studies considered Geographic Information Systems (GIS) tools for spatial decision-making in urban areas, along with energy planning [12]. GIS enables planners to visualize and analyze robust models that simulate real-world problems across different scenarios and situations [13]. It is used to optimize transport, plan infrastructure, and assess the relationship between land use and transport [14]. The integration of Multi-Criteria Decision Analysis (MCDA) and GIS tools is considered a hot topic for addressing and assessing complex planning problems. The GIS AHP tool was used to address conflicting criteria [15]. The Analytic Hierarchy Process quantitatively assesses subjective opinions by using pair-wise matrices to assign weights to each criterion [16]. Due to the effectiveness of GIS and AHP, they are used to optimize the placement of EV charging stations [17–19]. Such hybrid models enable balanced decisions by considering economic, technical, social, and environmental factors [20].

The global trend of attraction towards EV charging and e-mobility is a testament to the multiscale, geographically weighted regression model used in Wuhan, where the

location of charging stations and charging facilities are strong, dominating factors in the spatial heterogeneity across the city, particularly in the traffic zones [21]. At the district level, the viability of EV infrastructure is considered fundamentally important and is conditioned by district characteristics, including building density, energy ratings, and EV penetration rates [22]. An activity-based model in which the behaviour of the driver and EV infrastructure provisions play a vital role in the attraction and adoption of EV trends [23].

2. Global and Local Perspectives on EV Infrastructure

The global shift towards EVs aligns with infrastructure, charging stations, and a supportive environment, all of which are directly relevant to EV consumers and support national decarbonization targets [24]. Many countries focus on shifting from conventional engines to EVs through technological advancement, policy integration, and infrastructure and spatial planning. Countries such as the United States, China, Germany, and Norway build infrastructure by coordinating data-driven charging-station installation and linking policy incentives to transportation policies at the planning stage [25,26]. The optimal locations for EVs were analyzed and assessed using GIS and MCDA, incorporating spatial and non-spatial variables [27]. However, persistent issues such as weak institutional coordination, limited grid capacity, and uncoordinated urban planning complicate implementation.

As electric mobility trends and infrastructure grow in many regions, especially those with emissions problems, researchers have approached the location of electric vehicle (EV) charging stations as a combinatorial facility location problem [28], seeking optimal facility placement among possible sites. This began with the introduction of the flow-capturing location model, a method that identifies strategic points to capture vehicle flow [29]. Over time, this model evolved into the flow refuelling location model, tailored to the refuelling needs of alternative fuel vehicles. Various mathematical and complex models have since been introduced, such as bi-level optimisation, integer programming, and stochastic modelling approaches, to address the charging station location problem (CSLP) [30]. However, these models generally require advanced expertise in mathematical modelling, detailed analysis, and access to complex datasets. In addition to these mathematical approaches, different studies have suggested and evaluated methods for EV infrastructure planning, site suitability, and optimisation. These often employ GIS and MCDM frameworks. Data availability often limits these efforts and constrains the use of classical optimisation models [31].

In addition to classical formulations, recent research has advanced toward dynamic, traffic-aware, and grid-coupled optimisation. Discrete stochastic modelling captures the interactions between charging stations and fleet operations under dynamic road-traffic congestion, demonstrating how charging demand varies temporally and spatially across urban networks [32]. Equilibrium, traffic-aware placement of extreme-fast-charging infrastructure incorporates network-level travel-time effects, revealing that beyond a certain station density, additional facilities provide diminishing travel-time benefits and that network-based placement strategies outperform node-based schemes [33]. Charging networks are also modelled as cyber-physical systems integrated with smart grids, which enables active load balancing across multi-microgrid environments and underscores the necessity of embedding grid hosting-capacity constraints in station planning [34]. These methodologies rely on granular, real-time traffic and load-flow datasets, which are currently unavailable at the sector level for Islamabad. Consequently, the present GIS–MCDA framework serves as a pragmatic, initial solution for a data-scarce context rather than a state-of-the-art optimization model. As traffic counts and utility load data become more robust, future iterations may incorporate traffic-equilibrium and grid-coupled modelling, building upon the foundations established by these studies.

These infrastructure encounters highlight universal gaps. Drawing on international lessons, developed economies typically use GIS-based models for planning, whereas governments in developing countries often lack systematic approaches. In Pakistan, EV guidelines and policy were established in 2020, but there is still no scientific framework for infrastructure planning and placement, leading to inefficiency and underuse of infrastructure. If there is no rule and no clear placement policy, this will create a gap in EV adoption, and such psychological factors will also influence consumer confidence in adopting EVs. Unreliable electric grids, rapid and unplanned urbanization, financial constraints, and a lack of clear land-use and interaction policies pose a huge challenge for a country. People are interested in investing in the EV sector, including individual investors, and different utility companies respond to local demand rather than following an integrated plan. But encouraging and integrating EV adoption into the national transport policy could help forecast EV adoption and infrastructure needs [35]. Such a clear vision and approach ultimately encourage investors, ensure the deployment of EV infrastructure, and represent a step towards sustainability [36].

The Geographic Information System (GIS) is a powerful tool widely used to help planners resolve complex spatial relationships, identify demand patterns, and support evidence-based decision-making [37]. GIS-based planning was established to evaluate population density, assess accessibility, and assess site feasibility. In Europe, GIS and MCDA (Multi-Criteria Decision Analysis) were used to select optimal station sites, integrating economic, social, and technical criteria. Another study illustrated that GIS could deliver at the planning level, at the Micro (small-scale) and Macro (large-scale) levels, to ensure transparency and guide planners and policymakers in future planning [38].

There is no clear vision or policy for EVs in Pakistan, as the country faces methodological hurdles, including institutional and policy constraints, limited data, a lack of charging stations, and a lack of coordination among agencies and stakeholders. The attraction towards EVs is commendable, but uncoordinated coverage raises consumer anxiety & deters EV investment, even in the presence of strong purchase incentives [39]. To identify EV charging stations in Islamabad, GIS and MCDA methods have been adopted. Through different learning, the tools are scientifically and globally used for planning, design, and site suitability.

The GIS and AHP frameworks are used globally; however, their application in Pakistan has been limited. Previous studies have focused on EV purchase intentions, policy and institutional barriers [40], and broader sustainable mobility strategies [41,42], rather than sector-level spatial suitability. The current study uses GIS and AHP to analyse the suitability of EV charging stations in Islamabad. The study makes three key contributions: it combines an expert-weighted, five-criterion model with a sector-resolved Composite Suitability Index tailored to Islamabad's sector-and-zone structure; it connects suitability classes to a phased deployment roadmap aligned with the National Electric Vehicle Policy (NEVP) 2020 and the CDA Master Plan; and it includes a weight-and-threshold sensitivity analysis relevant to developing-country contexts, where such validation is rarely reported. The claim of being "first for Islamabad" refers specifically to the sector-level, multi-criteria spatial suitability model, not to methodological innovation in GIS–AHP.

3. Research Methods

The systematic framework identifies optimal sites for charging electric vehicle (EV) stations in Islamabad. It provides a technical description of the methods used and justifies the chosen strategies. This helps ensure that the findings are credible and replicable [43]. Figure 1 illustrates how the methodological framework brings coherence to the process. Planning EV infrastructure is complex, as spatial, technical, economic, and social factors

interact strongly. To address the complexity, different techniques are being used to identify and locate a suitable location for the EV. The previous research considered GIS and MCDM as different models to identify the location. Such as GIS, which stores, processes and visualizes data and MCDA, which allows you to evaluate several, mostly conflicting, criteria systematically. MCDA integrates both quantitative and subjective data, and the combination provides a scientifically based, scalable and clear model [44].

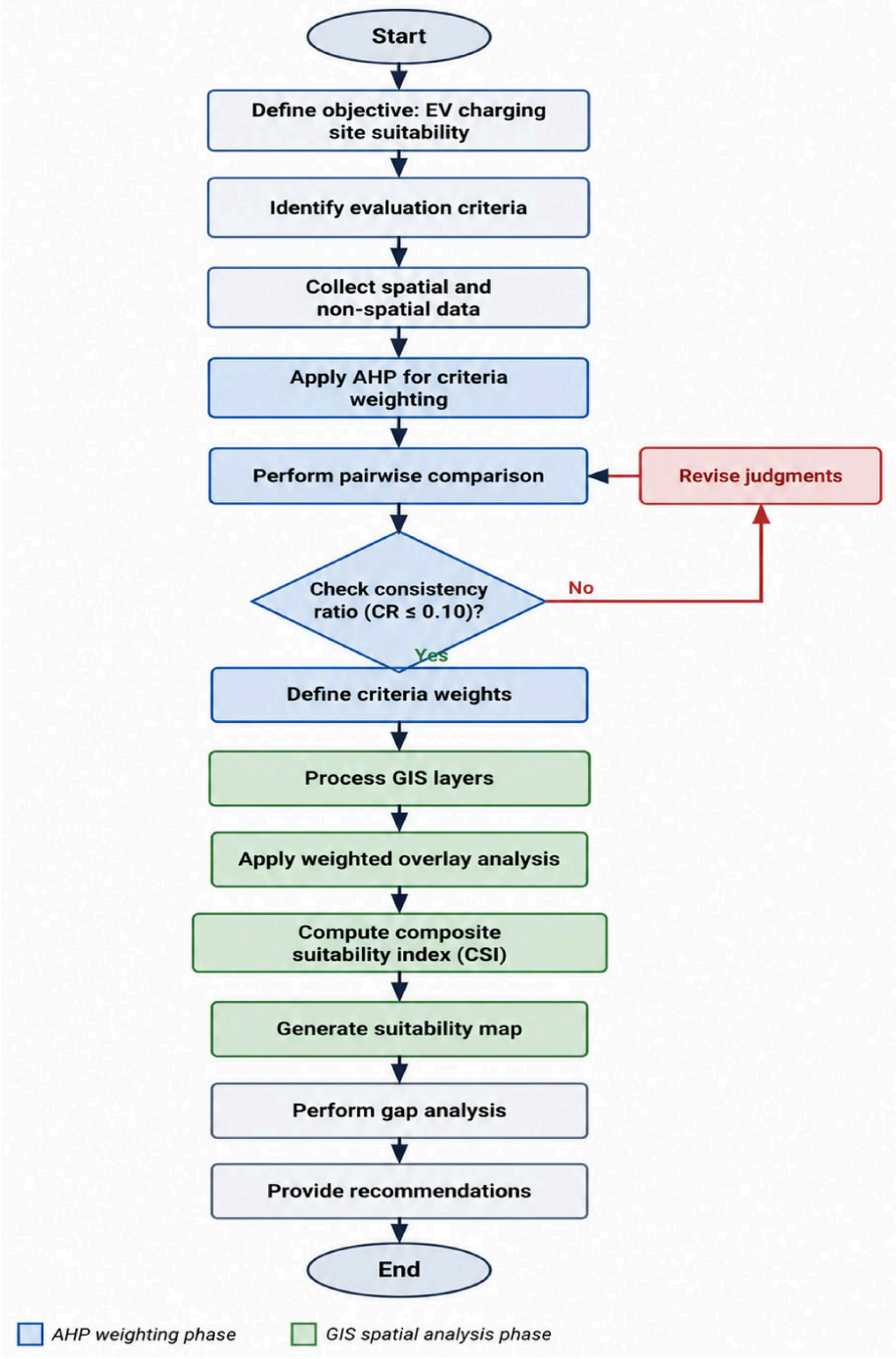


Figure 1. Research design of the study.

3.1. Study Area: Islamabad

Islamabad, the capital city of Pakistan, is considered as the case study for this research. Developed in the 1960s as a well-planned city, it features an arranged grid-based road network and zoned land-use sections, resulting in less congestion than Karachi or Lahore.

Situated on the Potohar Plateau at the bottom of the Margalla Hills, Islamabad covers about 906 square kilometers. It is separated into sectors and zones, each nominated for residential, industrial, commercial, or institutional use, making Islamabad one of the country's most systematically organized urban centers. This section establishes the research's credibility by highlighting robust data supporting the GIS-MCDA framework. The essential datasets of spatial and non-spatial from government departments, open-source agencies, and academic literature form the basis for assessing suitable EV charging sites in Islamabad. These spatial data enable analysis of the city's physical, demographic, and infrastructural features.

3.2. Data Sources and Acquisition

The GIS-MCDA framework is credible due to the synthesis of spatial and non-spatial data, which is obtained with the help of government services and open-source applications. According to the spatial analysis, socio economic data the study has been divided in different factors considered on the basis MCDM, as shown in Figure 2.

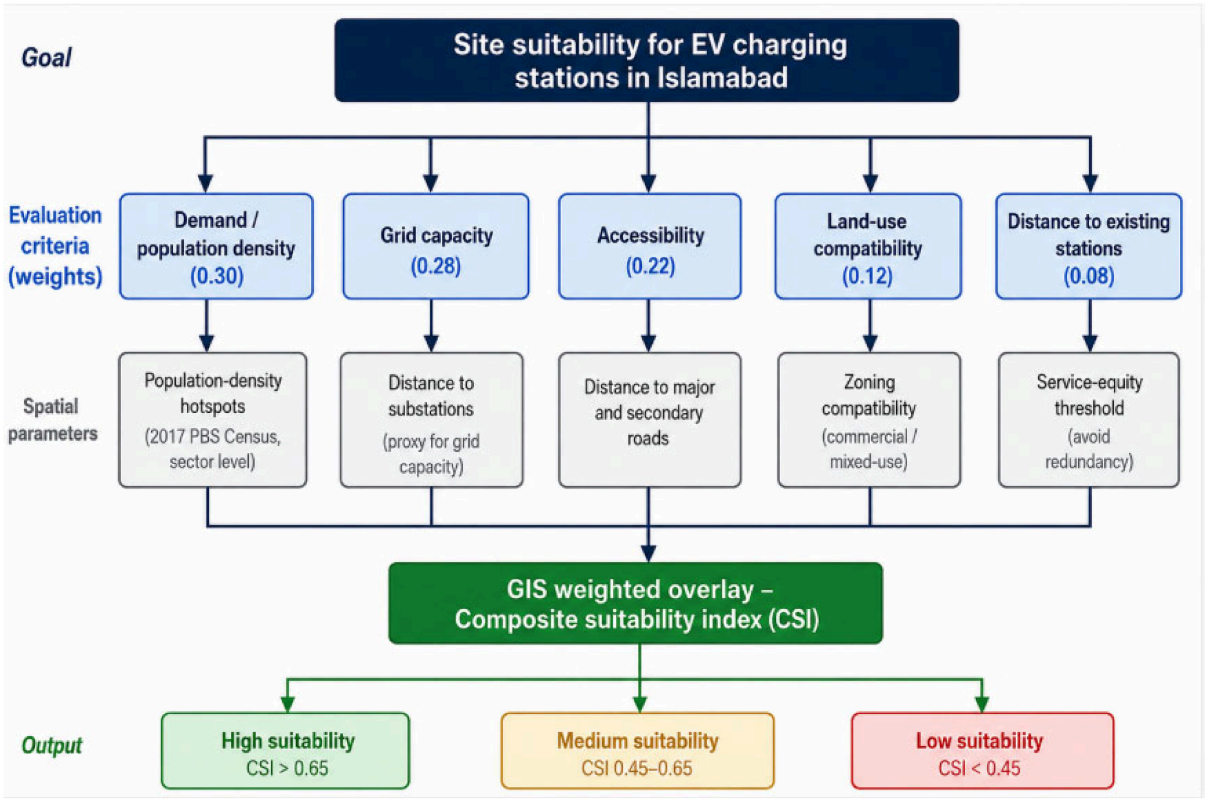


Figure 2. AHP criteria hierarchy for EV charging-station site suitability, showing the five criteria used, their spatial parameters, and the composite suitability index (CSI) output.

The main data layers that will be used in this study include:

- Infrastructure & Accessibility: OpenStreetMap (OSM) was used as the source of road network data, which were then compared to Capital Development Authority (CDA) maps to be accurate in the analysis of proximity.
- Demographics & Demand: Population density data were sourced from the most recent census and demographic records from the Pakistan Bureau of Statistics (PBS). The population-density layer (Figure 6), demand-suitability classification (Table 5), and the resulting Composite Suitability Index were derived from the 2017 Population and Housing Census, which is the most recent official source providing sector-level figures for Islamabad. These data were rescaled to match district-level 2023 PBS digital-census totals where available and interpolated to the 100 m analysis raster.

Due to the unavailability of sector-resolved 2023 micro-data, intra-sector distribution continues to rely on the 2017 Census. As a result, absolute demand figures, such as the 12% of the city exceeding 8000 persons/km^2, are subject to a degree of uncertainty. Accordingly, high-demand rankings should be regarded as robust in relative rather than absolute terms.

- Land Use & Zoning: Zoning data of the CDA officials was used to make sure that potential charging locations do not contradict residential, commercial, and industrial laws.
- Capacity of the grid: Data about the power infrastructure, such as the position of the substations and the capacity of the distribution lines was obtained at WAPDA and NEPRA to determine the technical feasibility and limit the installation expenses.
- Current Facilities: The sites of current fuel stations and existing EV chargers were overlaid with to find gaps in services and to avoid infrastructure redundancy.
- Policy: The strategic targets and methodological benchmarks of the study were given using Policy and Literature: The National Electric Vehicle Policy (NEVP) 2020 and up-to-date academic literature.

3.3. Selection of Criteria for Site Suitability

Evaluation criteria choice is a critical move in GIS-MCDA framework. Upon considering the best international practices and the local limitation of Islamabad city, there were five major criteria found in the suitability analysis:

- Accessibility: closeness to major and secondary road networks to make entrance and exit easy.
- Demand Density: Linkage to high-populated areas with the aim of maximizing the use of the station.
- Grid capacity is assessed by measuring the distance to existing electrical substations. This proximity serves as an initial indicator of the potential ease and cost of grid connection, rather than a direct measure of hosting capacity.
- Land Use Compatibility: Making sure the sites are situated in acceptable commercial or mixed-use areas.
- Service Equity: Strategic distance between the current fuel and charging stations to guarantee equal geographical distribution.

To contextualise the five-criterion model within the broader decision-making framework, a comprehensive set of dimensions, including economic, environmental, societal, technical, political, and traffic factors, was assessed for data availability, spatial measurability, and relevance to Islamabad. Sub-criteria without consistent city-wide spatial data, such as construction and land costs, electromagnetic-field exposure, tender frameworks, and subsidy schemes, were excluded from consideration. Consequently, the model was refined to include only the five operational criteria.

3.4. Analytic Hierarchy Process (AHP)

It is clear from the related studies that the Analytic Hierarchy Process (AHP) is applied to transfer expert judgments into reproducible, transparent criterion weights for the GIS-MCDA model. However, the studies also emphasize to suggest that the AHP moves in four steps: (i) hierarchically structure the problem, (ii) applying pairwise comparisons, (iii) measuring priority weights, and (iv) evaluating logical consistency [18].

Expert Panel and Questionnaire Procedure

A seven-member expert panel selection has been designed according to the established Analytic Hierarchy Process (AHP) method, where the pairwise judgments were formulated

by purposively chosen groups of domain specialists rather than large statistical samples. As per the AHP data collection guidelines, input must be credible and reproducible. Therefore, data were collected from seven experts relevant to the study. Among these, two were energy engineers with experience in WAPDA/NEPRA grid planning. Two were urban transport planners from the Capital Development Authority (CDA). Two were academics specialising in GIS-based spatial analysis and MCDA. One was an EV infrastructure policy advisor from the Ministry of Climate Change. All experts had 12 years of experience in their respective fields. In the first phase, pairwise comparison questions were shared electronically. Experts were briefed on selected criteria, which included Land-Use Compatibility, Accessibility, Population Density/Demand, Grid Capacity, and Distance to Existing Stations. According to the Saaty scale, a 9-point questionnaire was used for all comparisons ($n(n-1)/2 = 10$ pairs for five criteria). In the second review, the group shared responses during a joint expert review. To measure the consistency ratio (CR) of the experts, the Saaty standard threshold of 0.10 was asked to revise, review and adjust the score, according to the scale and standard. A comparison matrix was then created. The principal eigenvalue ($\lambda max = 5.27$), Consistency Index ($CI = (\lambda max - n)/(n-1) = (5.27-5)/(5-1) = 0.068$), and Consistency Ratio ($CR = CI/RI = 0.068/1.12 = 0.061$) were calculated using the standard eigenvector method. RI = 1.12 is the Random Index for n = 5 criteria (Saaty, 1980). Since CR = 0.061 is less than 0.10, the pairwise judgments are considered acceptably consistent.

The final matrix was generated through consensus during the second-round joint review, rather than by averaging independent matrices. Consequently, a separate inter-rater concordance coefficient, such as Kendall's coefficient of concordance, was not calculated. Agreement is demonstrated by the panel's convergence on a single matrix with a consistency ratio (CR = 0.061), which is well within Saaty's 0.10 threshold. The seven-member panel exemplifies the purposive, expertise-based sampling logic of the Analytic Hierarchy Process (AHP), wherein the credibility of judgments is derived from participants' domain expertise rather than statistical sample size.

3.5. GIS Integration and Spatial Analysis

The combination of Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) is the core of this research methodology. However, specific studies show that the GIS facilitates the visualization, manipulation, and assessment of spatial datasets, while AHP provides weighted values estimated from expert judgment when combined, these systems create suitability maps to support decision-making for electric vehicle (EV) charging station placement in Islamabad. Proximity measures, including distances to roads, substations, and existing stations, were calculated as Euclidean (straight-line) distances on a 100 m raster. This approach is justified by Islamabad's permeable, grid-based sector layout. Future research should consider network-based (shortest-path) distances to more accurately account for detours resulting from controlled-access corridors.

4. Data Analysis

The proposed study first adopted the Analytic Hierarchy Process (AHP) to measure the relative significance of five criteria accessibility, grid capacity, population density, compatibility with land use, and distance to existing charging/fuel stations based on expert judgment. The consistency ratio (CR = 0.061) was below the permissible value of 0.10, indicating consistent expert judgements. For the subsequent GIS-weighted overlay analysis, Table 1 summarizes the weights measured.

Table 1. Parameters and objectives.

Criterion	Parameter	Objective Link
Accessibility	Distance to major roads	Maximize user convenience
Population density	Demand hotspots	Ensure high utilization
Grid capacity	Proximity to substations	Ensure technical feasibility
Land use	Zoning compatibility	Regulatory compliance
Existing stations	Distance threshold	Avoid redundancy

λmax = 5.27, CI = 0.068, CR = 0.061 < 0.10, presenting acceptable consistency.

Figure 3 shows the location of Islamabad and its sector arrangement, focusing on its main roads. This map provides the context for the study area and serves as the source for further GIS analysis. To identify optimal locations for electric vehicle (EV) charging stations in Islamabad, the research then conducts an integrated composite suitability assessment. Finally, the underserved areas and their planning implications with a gap analysis are highlighted.

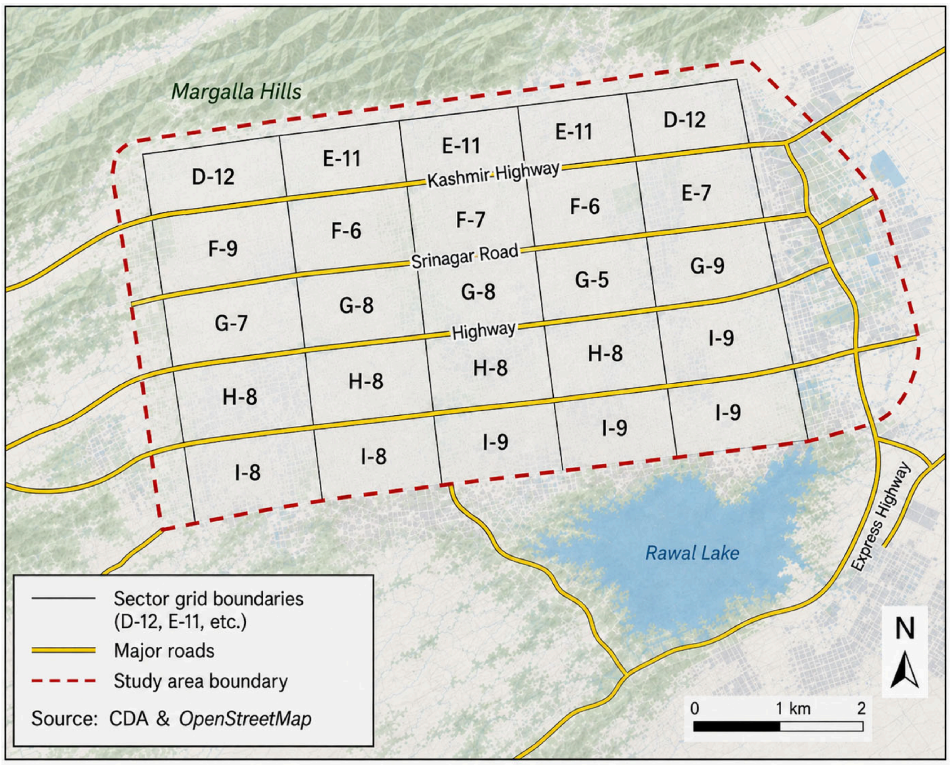


Figure 3. Location map of Islamabad showing residential sectors.

4.1. Data Preparation and Processing

The AHP analysis shows that the major determinants of EV charging station appropriateness in Islamabad, accounting for almost 60% of the model's impact, are population density (0.30) and grid capacity (0.28). This prioritization reveals that demand concentration and technical feasibility are the focus of infrastructure capability in developing markets. While accessibility is observed as second rank with a weight value (0.22). This keeps it significant in making the system convenient for users, so that technical and economic factors should be focused on during the initial placement phases. Furthermore, the compatibility of spatial equity and land use serves as a requisite regulatory filter. Overall, these findings indicate that while accounting for the grid's technical constraints EV rollout needs a strategic orientation toward high-demand urban cores, as shown in Table 2.

Table 2. Datasets and properties used in the analysis.

Dataset	Source	Type	Resolution	Use in Analysis
Road networks	OSM, CDA	Vector	100 m raster	Accessibility layer
Population density	PBS census	Raster	Sector-level	Demand estimation
Land use	CDA master plan	Vector	100 m raster	Land-use suitability
Electricity Infrastructure	WAPDA/NEPRA	Vector	100 m raster	Grid capacity and connectivity
Existing stations	Government/private firms	Point	Location- based	Gap analysis and redundancy check

4.2. Criteria Weighting Results

The Analytic Hierarchy Process (AHP) measures the significance of observed factors for multi-criteria decision analysis in geographic information systems (GIS). To fulfil the requirement, experts from transport policy, urban planning and energy utility sectors participate in structured pairwise comparisons. In this context, the study assesses five principal parameters: Accessibility, Grid Capacity, Demand, Land-Use Compatibility, and Distance to Existing Stations, as shown in Table 1.

Based on the weight allocation, two priorities emerge: comparing charging stations to demand centres and ensuring the technical feasibility of grid access. These priorities are related to one another. The argument comes from an expert that population concentration significantly affects utilization. Without a reliable power supply, regions with high demand cannot be sustainable. For operational convenience, the emphasis is on establishing these fundamentals: equity and regulatory requirements such as land-use restrictions and distance to existing structures. A basic product of this weighting practice serves asthe foundation for the weighted overlay investigation in GIS incorporating spatial datasets. The composite suitability index is created that blends both expert input and quantitative data. Thus, the final feasibility maps are grounded not only in data but also in reliable feasibility as presented in Figure 4.

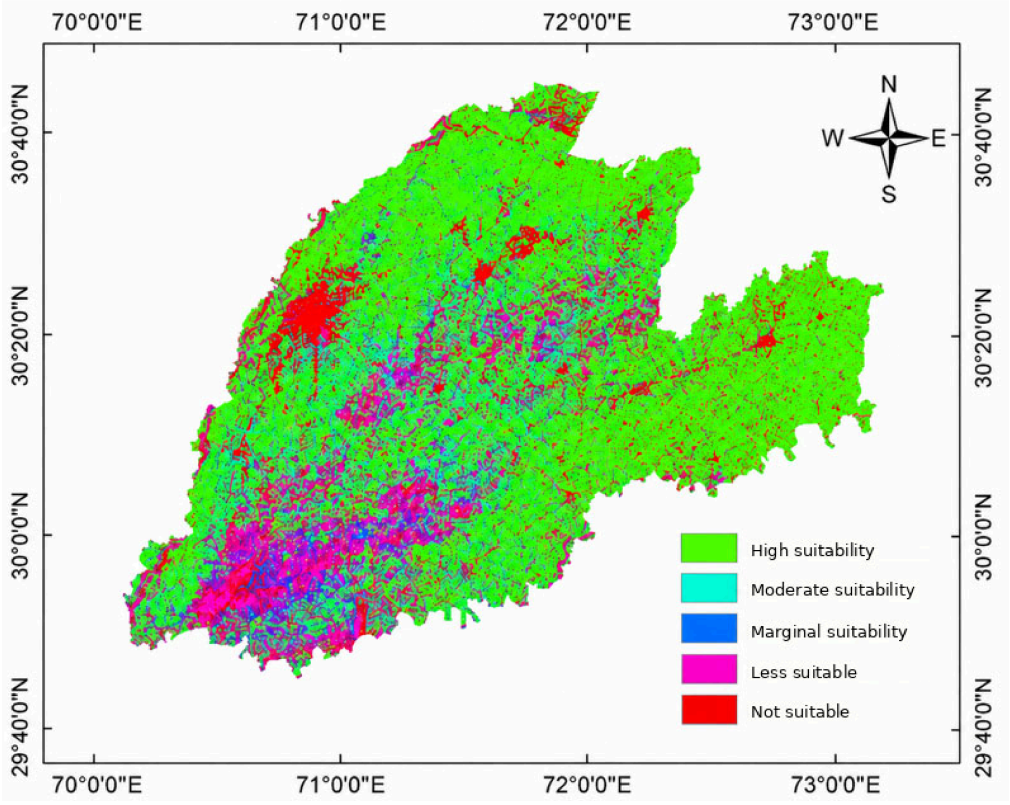


Figure 4. Areas analysed for station siting according to land suitability.

The relatively low weight assigned to Distance to Existing Stations (0.08) reflects the early stage of Islamabad's charging infrastructure, which currently includes few operational stations. At present, spacing from existing stations is a less significant determinant of site value compared to demand concentration, grid readiness, and accessibility. Within this model, the criterion primarily serves as a filter for service equity and redundancy avoidance rather than as a main driver of network coverage. As the charging network develops, the importance of this criterion is anticipated to increase. Sensitivity analysis demonstrates that reasonable increases in this weight do not alter the sector rank order.

4.3. Spatial Analysis Results

The five most significant criteria were evaluated using spatial analysis: accessibility (Figure 5), population density (Figure 6), grid infrastructure (Figure 7), land use (Figure 8), and existing fuel/charging stations. They were ranked and as shown in Table 3. Based on considering each criterion and processing in GIS independently, it was presented in thematic maps and recategorized into suitability criteria. The horizontal and vertical axes denote the row and column indices of the 100 m analysis raster rather than geographic coordinates; the underlying layers are georeferenced to Islamabad's projected coordinate system (UTM Zone 43N).

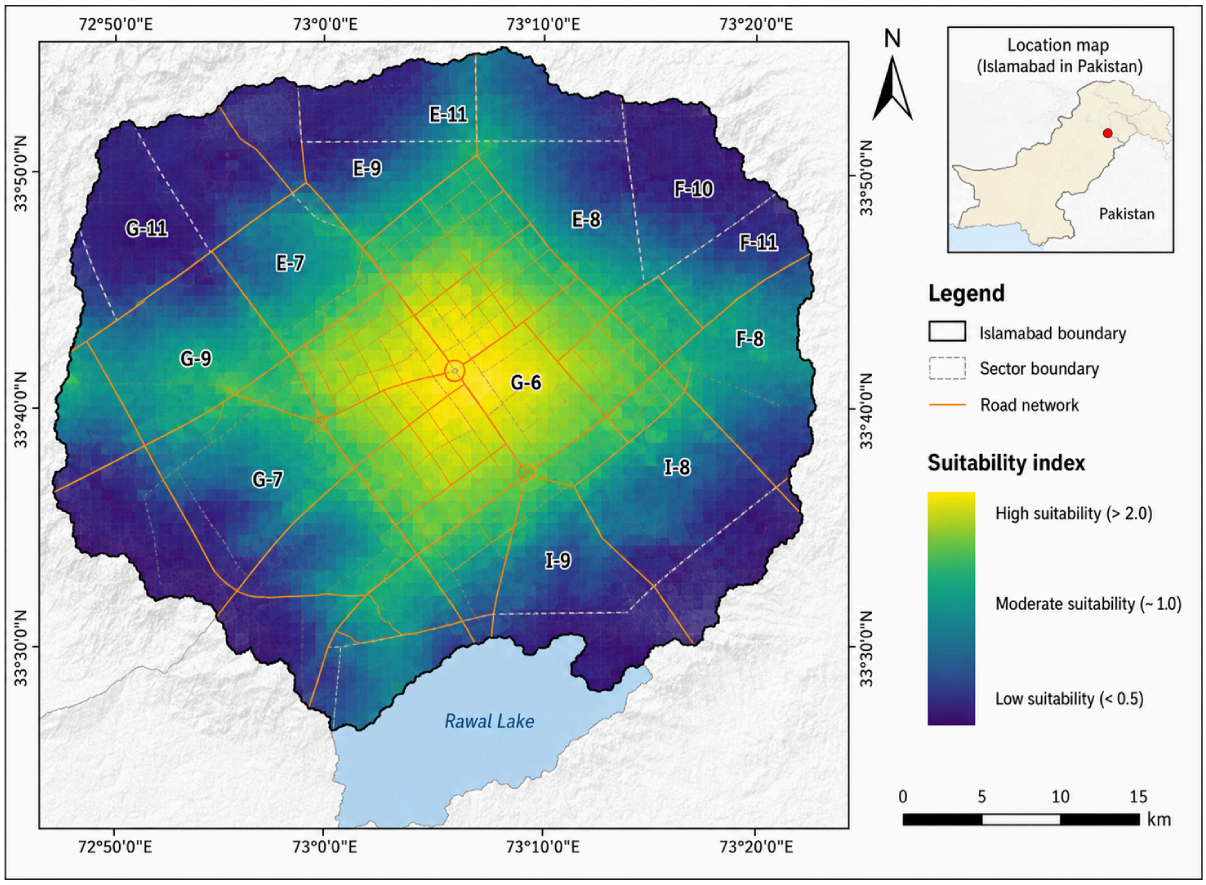


Figure 5. Accessibility suitability map for EV charging station site selection in Islamabad.

The importance of central corridors for early deployment is highlighted, as they offer easy access and high visibility for EV users. Usingsector-based density grids using derived from interpolated census data, the analysis identified commercial areas and high-density residential areas, such as G-6, G-7, G-9, and the Blue Area, as principal demand hotspots. The highest suitability rating is assigned to these locations. In contrast, lower population densities is assigned to peripheral areas like Bhara Kahu and Bani Gala, which are rated

as less suitable. The additional information on sustainability and accessibility criteria is summarized in Table 4.

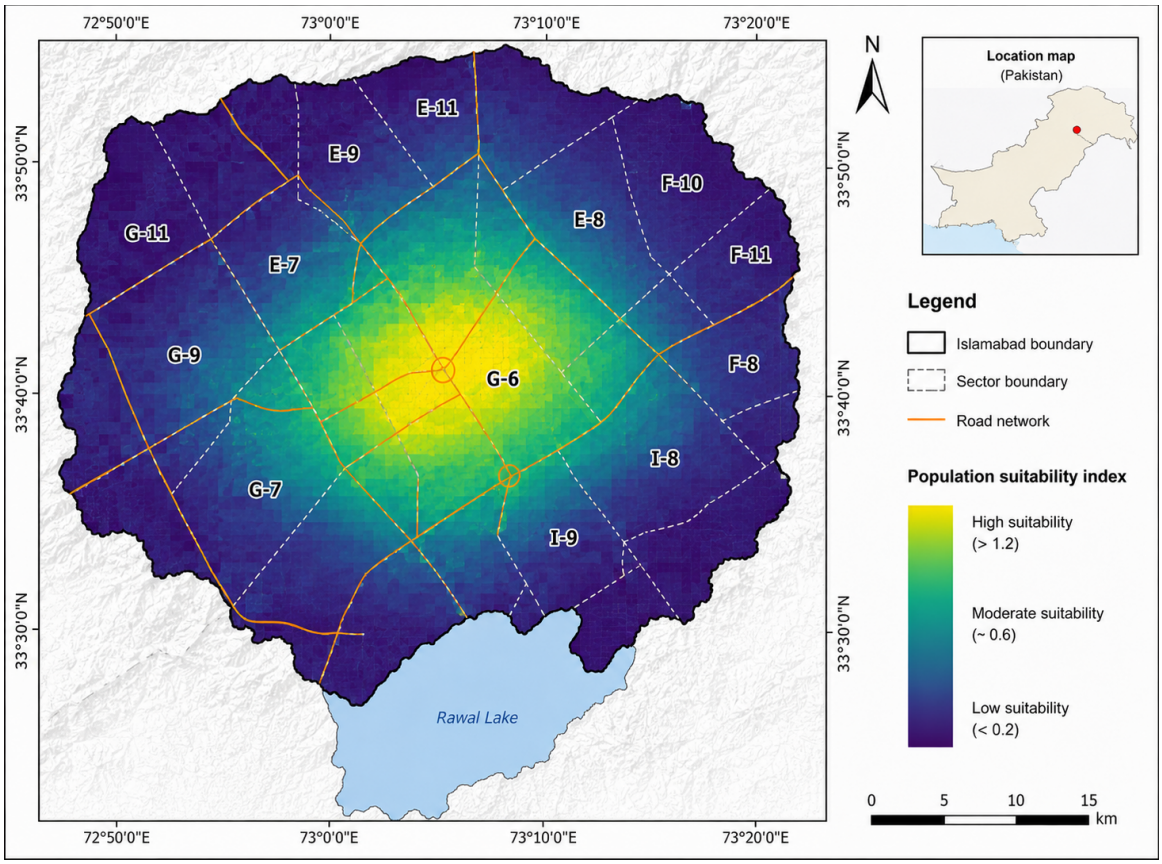


Figure 6. Population-density-based suitability map for EV charging station site selection in Islamabad.

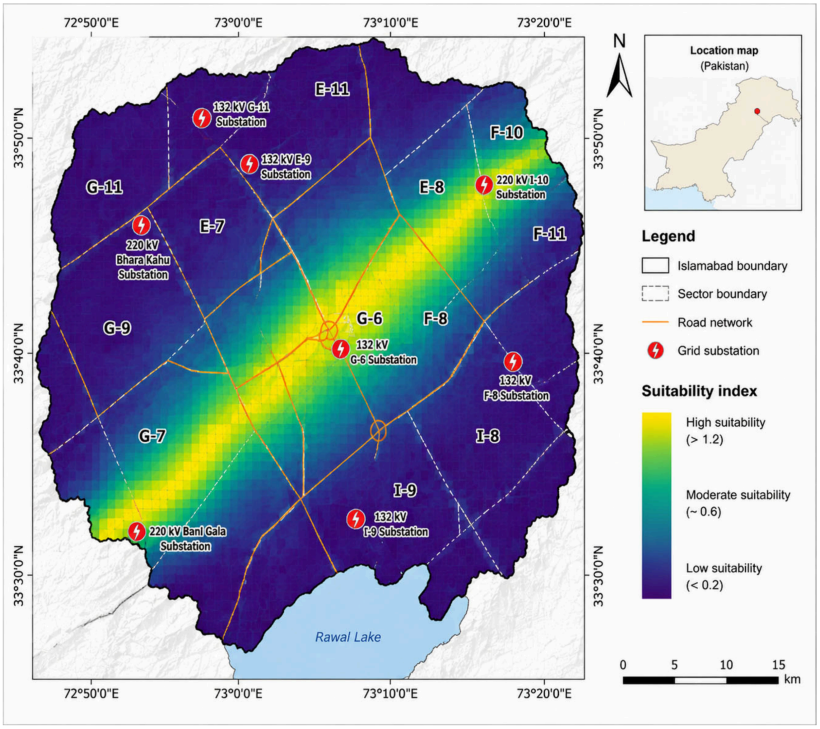


Figure 7. Grid-infrastructure suitability map for EV charging station site selection in Islamabad.

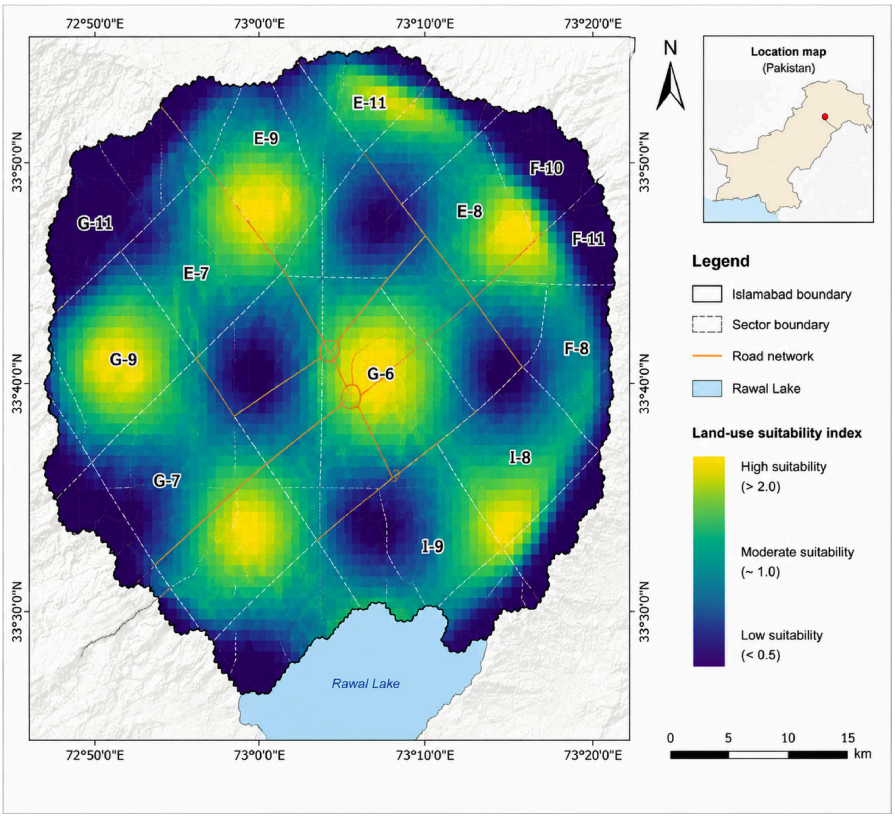


Figure 8. Land-use suitability map for EV charging station site selection in Islamabad.

Table 3. Final weights for criteria (AHP results).

Criterion	Weight	Rank
Demand (population density)	0.30	1
Grid capacity	0.28	2
Accessibility (roads)	0.22	3
Land-use compatibility	0.12	4
Distance to existing stations	0.08	5

Table 4. Accessibility suitability classification.

Distance to Roads	Suitability Score	% of City Area
<500 m	5	28
500 m to 1000 m	4	24
1000 m to 1500 m	3	20
1500 m to 2000 m	2	15
>2000 m	1	13

- Distance to substations was adopted as a preliminary spatial suitability indicator.
- Assessing actual grid hosting capacity requires detailed utility-level analysis of transformer loading, feeder capacity, voltage stability, and peak demand.
- Future studies should use real-time utility and load-flow data to improve the technical evaluation of EV charging infrastructure feasibility.

As shown in Table 5, a population density exceeding 8000 persons/km^2 covered 12% of the city's landreflecting areas of concentrated demandin Comparision about 11% has densities below 1000 persons/km^2. According to the distribution, central Islamabad is likely to experience the highest initial demand for EV charging infrastructure. To support

ssessment and evaluate grid capacity, substations and distribution lines were mapped. The most suitable areas considered were located within 1 km of substations. The strong grid support along the Blue Area corridor and in sectors G-10 to G-13 were highlighted in the analysis, while limited access to nearby substations was observed along peripheral residential areas. Detailed population density statistics are provided in Table 5. Based on the Table 6, which reports that 45% of Islamabad lies within 2 km of a substation, highlighting substantial grid coverage in urbanized areas.

Table 5. Population density statistics.

Population Density (Persons/km^2)	Suitability Score	% of City Area
>8000	5	12
5000 to 8000	4	22
3000 to 5000	3	30
1000 to 3000	2	25
<1000	1	11

Table 6. Grid infrastructure suitability.

Distance to Substations	Suitability Score	% of City Area
<1 km	5	18
1 km to 2 km	4	27
2 km to 3 km	3	25
3 km to 4 km	2	20
>4 km	1	10

Table 7 indicates that 22% of Islamabad is suitable for the development of charging infrastructure, whereas 15% of the area is excluded to ensure compliance with zoning requirements and to prevent conflicts with existing land-use policies. Following the identification of these zones, the distribution of fuel stations and EV charging points was analyzed to evaluate redundancy and to identify areas lacking adequate service. The results show a clear concentration of facilities in the Blue Area and around petrol stations in G-7 and F-8. Meanwhile, the I-sectors and peripheral residential areas remain largely underserved.

Table 7. Land-use suitability analysis.

Land-Use Type	Suitability Score	Coverage (%)
Commercial & mixed-use	5	22
Institutional	4	15
Industrial	3	10
Residential	2	38
Restricted/protected	0	15

Based on this investigation, which underlines the uneven nature of current infrastructure and the need for equitable expansion. By overlaying existing facilities with accessibility maps and population density, the study identifies peripheral gaps that require targeted investment to achieve abalanced network analysis.

The existing station suitability layer indicate, that the spatial distribution of existing fuel and EV charging stations, as shown in Figure 9. The area with greater suitability were selected criteria where the existing-station criterion helps identify potential charging-station sites while accounting for existing service coverage and spatial gaps.

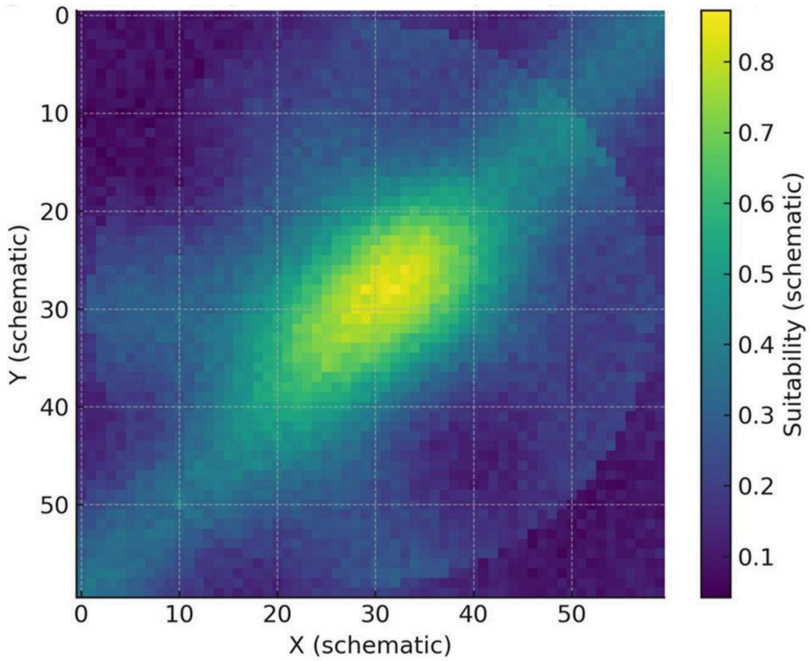


Figure 9. Distribution of existing stations.

4.3.1. Composite Suitability Analysis

To integrate layers, including spatial accessibility, demand, grid capacity, land use, and existing stations into a single decision-support system, the analysis consists of several steps. In the first step, each layer is developed within the GIS environment. Next, the Analytic Hierarchy Process (AHP) weights are associated with each layer. Then, based on these weights, a weighted overlay analysis combines the specified layers. This study approach incorporates both quantitative spatial data and expert judgments into the final suitability outcomes. Finally, the results of the AHP analysis are presented in Figure 10.

- Demand (Population Density) = 0.30
- Grid Capacity = 0.28
- Accessibility = 0.22
- Land-Use Compatibility = 0.12
- Distance to Existing Stations = 0.08

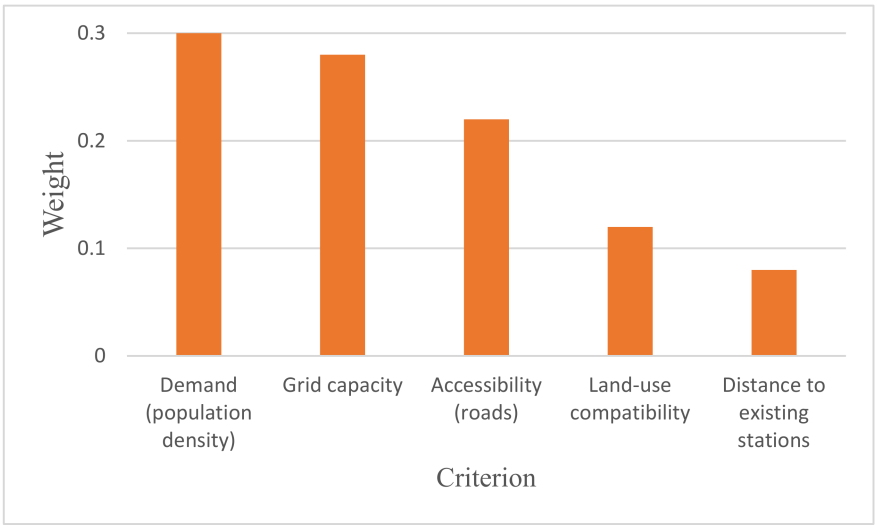


Figure 10. Composite suitability index (CSI) map from the GIS weighted overlay AHP-derived weights of the five criteria used in the GIS-MCDA model.

A Composite Suitability Index (CSI) for each raster cell inIslamabad was generated using a weighted overlay. This reflects the cumulative suitability of locations for EV charging station placement. High-suitability zones are identified to concentrate in the central G- and F-sectors. Also, the study identified further areas along major transport corridors such as the Islamabad Expressway and Murree Road. These regions are rated high due to overlapping accessibility, demand, and grid coverage. The H- and I-sectors are identified as medium-suitability zones, with moderate grid availability and population density, but accessibility remains adequate. Low-suitability zones such as Bani Gala, Bhara Kahu, and the Margalla foothills occur primarily in outlying and rural areas, where population density and grid access remain inadequate. Table 8 provides the Composite suitability classification.

Table 8. Composite suitability classification.

Category	CSI Range	% of City Area	Characteristics
High suitability	>0.65	26%	Dense population, strong grid, road proximity
Medium suitability	0. 45–0.65	41%	Moderate demand, mixed land-use, partial grid access
Low suitability	<0.45	33%	Sparse population, weak infrastructure

Based on these results, about one-quarter of Islamabad's land is ideal for immediate deployment. Much of the rest is only moderately suitable and will need focused upgrades. The urban core, which consistently scores highest due to overlapping demand, road density, and grid capacity, should be prioritized for EV charging stations. Mid-ring sectors (I sectors and the edges of G sectors) are moderately suitable and can be phased in as demand increases, At the same timethe periphery and rural outskirts are less suitable. These edge and rural sites may need coverage in the future, but are not cost-effective now.

CSI classification thresholds (CSI > 0.65 for High Suitability, 0.45–0.65 for Medium Suitability, and <0.45 for Low Suitability) were determined via three complementary methods to ensure scientific rigour. First, a natural-breaks (Jenks) classification algorithm was applied to the continuous CSI raster output to identify statistically optimal breakpoints that minimise within-class variance and maximise between-class variance. The Jenks algorithm independently suggested threshold values of approximately 0.44 and 0.64, closely aligning with the adopted boundaries. Second, the thresholds were cross-validated against established benchmark thresholds used in comparable GIS-MCDA suitability studies in South and Southeast Asian urban contexts, where analogous tri-class schemes commonly use the 0.40–0.45 and 0.60–0.65 range as demarcation points [14,23]. Third, the draft thresholds were reviewed and confirmed by the expert panel during the second-round questionnaire; experts were asked whether the provisional breakpoints correctly separated areas they would professionally classify as "immediately deployable," "conditionally suitable," and "not currently viable." Consensus was reached on the presented values with no substantive revision requested. This multi-method approach ensures that the classification boundaries are data-driven, contextually validated, and expert-endorsed, rather than arbitrarily assigned. The Jenks algorithm found threshold values of about 0.44 and 0.64, which are very close to the chosen boundaries. These values were rounded to 0.45 and 0.65 to make the cut-offs on the 0–1 CSI scale clear and easy to use. This small adjustment, less than 0.01 in CSI units, changes the classification of only a tiny number of raster cells and still fits within the ±20% threshold.

1. Immediate Deployment (High Suitability): It tends to rank central and corridor sectors with robust alignment of demand, grid, and accessibility.

2. Medium-Term Deployment (Moderate Suitability): It is persuaded to **invest in** grid upgrading and accessibility in mid-ring zones.
3. Long-Term Deployment (Low Suitability): It is more probable to expand gradually in peripheral and rural areas as more people use EVs. According to the outcomes above, the GIS-MCDA outputs will therefore **serve** as a diagnostic instrument, i.e., demonstrating the locations of gaps, and as a planning tool, i.e., indicating where **interventions are** intended to be administered over time.

4.3.2. Gap Analysis

As the composite suitability analysis identifies ideal locations for EV charging stations, it is essential to assess how these results align with the current distribution of charging and fueling infrastructure. This gap analysis method identifies underserved regions of prospective demand lacking charging infrastructure, enabling planning to proceed. These steps address the dual imperatives of efficiency and spatial equity. To validate the effects of the suitability analysis, after the composite suitability map was overlaid on the layers of existing stations, it became clear that the dissemination varied. Based on current charging point situation, it is evident that these areas already provide durable road accessibility, high demand, and grid connectivity, which are clustered in the Blue Area and nearby sectors such as G-7, F-8, and F-10. As many high-suitability centers in the urban core are already well served, specified infrastructure concentration, and redundancy are presented here. However, regions such as I-9, I-10, and G-11 show high or medium suitability but presently lack suitable charging facilities. Similarly, the southern corridors along the Islamabad Expressway, such as I-8 and I-9 sectors, remain underserved, which show increasing population densities and strong grid potential. The peripheral residential clusters in Bhara Kahu and Bani Gala face infrastructure gaps but also show moderate suitability.

- High demand but unserved zones: The regions such as G-9 and I-10 tend to involve densely populated residential regions, which are highly suitable, but deficient in charging stations. These zones should be ranked for short-term placement.
- Medium-suitability growth corridors: The regions such as I-8, G-13, and H sectors, which have adequate grid and road access. Increasing population densities, tend to signal medium-term prospects in these areas.
- Peripheral underserved communities: The study identifies a need to prioritise high-suitability zones such as G-9 and I-10, for short-term arrangement of EV charging stations. Given their growing populations and improving infrastructure, the Medium-suitability growth corridors such as I-8, G-13, and H- sectors should be reflected in medium-term planning. To promote equitable EV access, the outlying neighborhoods like Bhara Kahu, Tarnol, and Bani Gala, despite existing low demand, deserve long-term investment. Planning should focus beyond underlining zones with current high-demand centers and instead cover the gaps in the mid-ring and fringe areas. Strategic clustering of stations at defined infrastructure gaps will reduce spatial imbalance and range anxiety, promote accessibility, and ensure effective use of resources.

This gap analysis used a qualitative approach, as there are only a few public charging stations in Islamabad at present. It is worthwhile to estimate a reliable spatial hit rate for charger and power needs in underserved areas. As more data on charger locations becomes available, future studies will assess the accuracy of the predictions by comparing them to actual usage, such as the share of busy stations in high-suitability areas. These gaps will then be used to estimate how many chargers and how much power are needed.

4.4. Sensitivity Analysis

The GIS and MCDA model demonstrated robustness through a two-phase analysis. The initial phase evaluated the effects of criterion weighting, while the subsequent phase assessed variations in distance to roads and substations. Table 8 presents the suitability threshold range from high to low. The AHP was employed to analyze weight sensitivity, which ranged from ±10% to ±25% of the baseline. Based on the calculations and range variation, Demand and Grid capacity were set as the primary criteria. Their ranges were 0.30 and 0.28, respectively. The blue area, located in sectors G-10 and G-13, had strong and consistent grid coverage, as shown in Table 6. Accessibility was moderate at 0.22, with land use compatibility at 0.12, and distance to the existing station at 0.08. Sectors G and F demonstrated the highest population-based spatial core suitability. Distance-threshold sensitivity scenarios were compared with baseline scenarios, as detailed in Tables 4 and 6.

The high suitability covers 22% to 29% of the area, the medium suitability class covers 39% to 43%, and the low suitability class covers 31% to 35%, as shown in Table 9. Sector rankings remain consistent, with the central G and F sectors demonstrating the highest suitability. Conversely, peripheral areas such as Bani Gala, Margalla foothills, and Bhara Kahu consistently show low suitability. In each scenario, when a single criterion weight was altered by ±10% or ±25%, the remaining four weights were proportionally adjusted to maintain a total sum of one. Each unchanged weight w_i was rescaled using the factor $(1 - w'_k)/(1 - w_k)$, where w_k and w'_k represent the original and modified values of the varied criterion k. For distance, the threshold scenarios were those in which the weights remained constant, but the boundaries for road and substation distances were modified by ±20%. Table 9 also explains that, for each scenario, the modified weight or threshold, the proportion of the city in each suitability class, and any changes in sector rankings are provided. This analysis evaluates variations in each criterion weight (±10% and ±25%) and the distance threshold (±20%). The high suitability is 22–29%, medium 39–43%, and low 31–35%, as explained in Table 9. These findings indicate that the primary G- and F-sector rank order remains consistent.

Table 9. Sensitivity analysis scenarios and outcomes.

Scenario	Modified Weight/Threshold on the Basis of Weight	High (%)	Medium (%)	Low (%)	Sector-Level Ranking
Baseline	D 0.30, G 0.28, A 0.22, L 0.12, E 0.08	26	41	33	G and F sectors highest (reference)
Demand +25%	D 0.375 (weights re-normalized)	29	40	31	D sector overtakes; G/F drop to 2nd–3rd
Demand −25%	D 0.225 (weights re-normalized)	23	42	35	NM—G and F remain highest
Grid capacity +25%	G 0.350 (weights re-normalized)	28	40	32	NM—G and F remain highest
Grid capacity −25%	G 0.210 (weights re-normalized)	24	42	34	NM—G and F remain highest
Accessibility +25%	A 0.275 (weights re-normalized)	27	41	32	NM—G and F remain highest
Distance thresholds −20%	Road and substation class breaks −20%	22	43	35	NM—G and F remain highest
Distance thresholds +20%	Road and substation class breaks +20%	29	39	32	NM—G and F remain highest

D = demand (population density), G = grid capacity, A = accessibility, L = land-use compatibility, E = distance to existing stations. In each weight scenario the perturbed criterion is shown and the remaining four weights are re-normalised to sum to unity.

The potential spatial correlation and double counting between demand, which is represented by population density and land use compatibility were considered during the model development. The dense residential areas may coincide with permitted land use zones; these layers capture distinct concepts that are established based on residential demand and charging infrastructure in Islamabad. The analysis also explained that the permissibility of residential G sectors has the highest demand but only moderate land-use

suitability, which is linked to commercial and mixed-use zoning. Conversely, some areas within the Blue Area show high land-use suitability but only moderate residential demand. This partial separation reduces, but does not fully eliminate, the risk of overlap. To address this, future research should quantify the degree of dependence by calculating the pairwise Pearson correlations between the two suitability rasters and screening all criteria using variance inflation factors (VIFs) or principal component analysis (PCA). If redundancy is found, the relevant layers should be combined or re-weighted.

5. Conclusions

This study was designed to provide an efficient, evidence-based model to develop EV charging infrastructure in Islamabad. The current deficiency of coordinated planning was also addressed. The research utilized combined techniques such as GIS and the AHP within a MCDA framework. This framework provides policymakers with a clear, structured approach for identifying optimal locations for EV charging stations. The spatial, socio-economic factors and other technical factors were considered. It prioritizes accessibility, population demand, grid capacity, land-use compatibility, and the strategic placement of stations. Using of both expert judgment and quantitative data, the model finds that approximately a quarter of Islamabad's land area is immediately suitable for EV charging, mainly in central sectors such as G-6 to G-10, F-8, and the Blue Area. The Medium-suitability zones such as I-8, I-9, G-11, and G-13, cover 41 percent of the city. An infrastructure upgrade is required in suburbs such as Bhara Kahu, Tarnol, and Bani Gala. The identification of both high-demand and underserved areas is the main contribution of the study, which outlines targeted policies and investments. Following the gap analysis, these phased policy recommendations align with Pakistan's NEVP 2020 and Islamabad's CDA Master Plan. In the short term (Years 1–2), CDA and AEDB should fast-track private-sector EV charging station licensing in G-9, G-10, and I-10, where population density and grid proximity are high, but infrastructure is lacking. Co-locate new stations with commercial nodes or petrol stations to reduce user anxiety and leverage footfall. In the medium term (Years 3–5), WAPDA and NEPRA should launch targeted grid upgrades in the H-sectors and G-13 corridor, increasing substation capacity to match projected EV demand under the NTDC expansion plan. Streamline planning permissions via the CDA's single-window desk for mid-ring sites. In the long term (Years 6–10), implement a cross-subsidy or viability-gap-funding system, potentially through the AEDB's EV infrastructure fund, to ensure equitable access in peripheral areas, including Bhara Kahu, Tarnol, and Bani Gala. This prevents spatial inequality as EV adoption grows.

The phased recommendations outlined here offer guidance regarding direction and sequencing rather than specifying final quantities. Determining the number of stations, charger power ratings, substation capacity, and conducting a cost benefit analysis of the cross-subsidy proposal requires access to utility load-flow and investment-cost data. These considerations extend beyond the scope of the current spatial suitability analysis and will be examined in a separate techno-economic study. This study provides Islamabad's first sector-level, multi-criteria GIS suitability analysis to guide phased policy. It connects spatial analysis to operational planning in a developing-country context, filling a gap. Future work should include real-time traffic data, financial models, and consumer surveys, and replicate this process in Karachi and Lahore for national comparison. A sensitivity analysis confirmed that the identified priority zones are robust, resulting in AHP criteria varying by $\pm 25\%$ and shifting the road and substation distance class boundaries by $\pm 20\%$. The result also supports and strengthens confidence in the planning recommendation.

Study Limitations

The model was validated internally using Jenks classification, benchmark thresholds, expert input, and sensitivity analysis, as well as spatially through gap analysis with existing fuel and charging infrastructure. However, external validation against observed EV usage or driver-preference data was not possible due to the unavailability of such datasets for Islamabad. Addressing this limitation remains a priority for future research.

The expert panel comprised institutional stakeholders, transport planners, including grid engineers, transport planners, GIS academics, and a policy advisor; however, EV individual owners and prospective users were not represented. Consequently, the assigned weights reflect a supply side, infrastructure-oriented perspective. Future model iterations should prioritise incorporating demand-side preferences through consumer and stated-preference surveys. The road network (OpenStreetMap) and land-use/zoning (CDA) layers were cross-checked, but independent ground validation was not conducted. Positional or classification errors within these datasets may influence the suitability analysis. Verification against field or cadastral records is therefore recommended. The sector-and-zone framework does not explicitly account for low-income and informal settlements (katchi abadis), whose residents may have distinct access requirements. A suitability-driven rollout may result in early investment being concentrated in more affluent central sectors. To advance spatial justice alongside technical efficiency, it is advisable to include a social equity criterion, such as assigning greater weight to underserved or lower-income settlements.

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