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Suitable Area Location Selection for Electric Vehicle Charging Stations with Fuzzy AHP: Balıkesir Example*

Bulanık Analitik Hiyerarşi Süreci ile Elektrikli Araç Şarj İstasyonları için Uygun Alan Yer Seçimi: Balıkesir Örneği

Mete Korhan Özköka[a], Gamze Karadaş[b], Esra Öztürk[c], Ilker Oruc[d]

[a] Kirklareli University, Faculty of Architecture, Urban and Regional Planning, Kırklareli, Türkiye. ORCID: 0000-0001-8734-3644

[b] Kirklareli University, Faculty of Architecture, Urban and Regional Planning, Kırklareli, Türkiye. ORCID: 0009-0005-9576-0823

[c] Kirklareli University, Faculty of Architecture, Urban and Regional Planning, Kırklareli, Türkiye. ORCID: 0009-0001-6945-2377

[d] Kirklareli University, Vocational College of Technical Sciences, Kırklareli, Türkiye. ORCID: 0000-0003-0359-8696

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Corresponding Author/ Sorumlu Yazar

M.K. Özkök
metekorhanozkok@gmail.com

www.gpt-studios.org

Abstract / Öz

The rapid proliferation of electric vehicles (EVs) necessitates the strategic planning of charging infrastructure to mitigate range anxiety and promote sustainable urban mobility. This study addresses the critical supply-demand imbalance in Balıkesir, Türkiye, where a remarkable 1895% increase in EVs between 2020 and 2024 has placed significant strain on the existing network. This study aims to identify the most suitable locations for new EV charging stations in the central districts of Karesi and Altıeylül. A hybrid methodology integrating the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and Geographic Information Systems (GIS) was employed. Eight criteria, derived from a comprehensive literature synthesis, were weighted using Fuzzy AHP to manage the inherent subjectivity in decision-making. These criteria included population density, traffic density, and proximity to main roads. The findings revealed that proximity to main roads (w = 0.239), population density (w = 0.217), and traffic density (w = 0.116) were the most influential factors. The model demonstrated a high consistency ratio (CR = 0.01753), confirming its reliability. The final suitability map identified central neighborhoods, such as Altıeylül and Oruçgazi, as high-priority investment areas due to their high suitability scores and low density of existing charging stations. This research is expected to provide a data-driven decision support tool for local governments and private investors, offering a strategic roadmap for the efficient allocation of resources and the effective expansion of Balıkesir's sustainable EV charging infrastructure.

Elektrikli araçların (EV) küresel ölçekte hızla yaygınlaşması, kullanıcıların 'menzil kaygısını' en aza indirmek ve sürdürülebilir kentsel hareketliliği desteklemek amacıyla şarj altyapısının stratejik olarak planlanmasını zorunlu kılmaktadır. Bu çalışma, 2020-2024 yılları arasında EV sayısındaki %1895'lik dikkat çekici artışın mevcut ağı zorladığı Balıkesir, Türkiye'deki kritik arz-talep dengesizliğini ele almaktadır. Çalışmanın temel amacı, merkezi Karesi ve Altıeylül ilçelerinde yeni EV şarj istasyonları için en uygun yerleri belirlemektir. Bu süreci incelemek için, Bulanık Analitik Hiyerarşi Süreci (Bulanık AHP) ve Coğrafi Bilgi Sistemleri'ni (CBS) bütünleştiren hibrit bir metodoloji kullanılmıştır. Kapsamlı bir literatür sentezinden türetilen ve nüfus yoğunluğu, trafik yoğunluğu, ana yollara yakınlık gibi unsurları içeren sekiz kriter, karar verme sürecindeki doğal öznelliği yönetmek amacıyla Bulanık AHP ile ağırlıklandırılmıştır. Sonuçlar, ana yollara yakınlığın (0,239), nüfus yoğunluğunun (0,217) ve trafik yoğunluğunun (0,116) en etkili faktörler olduğunu ortaya koymuştur. Model, güvenilirliğini kanıtlayan yüksek bir tutarlılık oranı (CR = 0,01753) elde etmiştir. Nihai uygunluk haritası, Altıeylül ve Oruçgazi gibi merkezi mahalleleri, yüksek uygunluk puanları ve düşük mevcut şarj istasyonu yoğunlukları nedeniyle yüksek öncelikli yatırım bölgeleri olarak tanımlamıştır. Bu araştırmanın, yerel yönetimler ve özel yatırımcılar için veri odaklı bir karar destek aracı sunarak, kaynakların verimli tahsisi ve Balıkesir'in sürdürülebilir EV şarj altyapısının etkin bir şekilde genişletilmesi için stratejik bir yol haritası sağlayacağı düşünülmektedir.

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1. Introduction

One of the most fundamental global challenges of the 21st century -the combating of climate change and the building

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of a sustainable future- necessitates a fundamental paradigm shift in the energy and transportation sectors worldwide. The establishment of carbon emission reduction targets in the context of international commitments, such as the Paris Agreement, has prompted countries to reconsider their reliance on fossil fuels and transition towards cleaner energy alternatives. In this transformation process, the transportation sector, a major contributor to urban air pollution and greenhouse gas emissions, is undergoing a restructuring through electrification. Electric vehicles (EVs) are regarded as the technological cornerstone of this green transition due to their zero tailpipe emissions, higher energy efficiency, and potential for integration with renewable energy sources (Farghali et al., 2023; Menyhart, 2024). Radical policies, such as the European Union's decision to ban the sale of new internal combustion engine vehicles from 2035 as part of its "Fit for 55", demonstrate that this transition is no longer a matter of choice but rather an inevitability (European Council [EC], n.d.; Menyhart, 2024). However, one of the most critical barriers to the widespread adoption of electric vehicles is users' fear of being stranded on the road without access to charging facilities, known as “range anxiety” (Khaleghikarahrodi & Macht, 2024). This anxiety is rooted in a charging infrastructure that is often inadequate, disorganized, and strategically unplanned (Lu et al., 2016; X. Liu, 2024). The successful establishment of an electric vehicle ecosystem in an urban environment entails more than merely increasing the number of vehicles on the roads. It is also contingent upon the creation of an accessible, reliable, and efficient network of charging stations to support these vehicles. Consequently, the optimal placement of charging stations is not merely an infrastructure planning issue; rather, it is a strategic decision that directly affects user satisfaction and confidence, maximizes the return on investment, and determines the overall success of the electrification transition (Karolemeas et al., 2021; Wei et al., 2022). This challenge entails considerably more intricate and multifaceted dynamics than the location logic of conventional gas stations, which predominantly concentrate on major traffic arteries.

The selection of optimal locations for electric vehicle charging stations is inherently a multi-criteria decision-making (MCDM) problem. Determining the optimal location necessitates a comprehensive evaluation of numerous factors that may conflict with each other. The aforementioned factors encompass demand-driven criteria (population density, traffic flow, socio-economic level), infrastructure and accessibility criteria (proximity to main roads, transformer stations, public transportation stops), geographical and environmental constraints (slope, terrain, protected areas), and urban integration factors (integration with existing parking lots, shopping centers, public service areas) (Alkan et al., 2023; Bilgilioğlu, 2022). The relative importance of these criteria in the decision-making process is subjective and often determined by the subjective judgments of the decision-makers. At this juncture, there is an imperative for scientific and systematic approaches to objectify the process and enhance the reliability of the results. The integration of Geographic Information Systems (GIS)-based spatial analyses with MCDM methods has been identified as a frequently preferred and proven effective approach to solving this complex problem in the extant literature (Erbaş et al., 2018; Güler & Yomralıoğlu, 2020; Kłos & Sierpiński, 2023). metekorhanozkok@gmail.com

Contemporary discourse indicates that this planning process encompasses more than merely the geographical placement of charging stations; it also necessitates the management of their impact on the urban power grid. The increasing prevalence of electric vehicles (EVs) has the potential to generate substantial peak loads on electrical grids, particularly during evening hours when individuals return home and recharge their vehicles. This phenomenon, termed "uncontrolled charging," has the potential to result in overloading of local transformers, voltage fluctuations, and even outages (C. B. Jones et al., 2021; Hossain et al., 2016; University of Strathclyde (UOS), n.d.). Consequently, contemporary charging infrastructure planning must encompass “smart charging” methodologies and Vehicle-to-Grid (V2G) technologies. Smart charging is a strategy that aims to reduce stress on the grid by shifting the charging process to times when the grid is most suitable. This can be achieved by adjusting the charging schedule to coincide with periods of low demand or high renewable energy production. V2G represents a significant advancement in this regard by leveraging the batteries of parked electric vehicles as small, distributed energy sources during sudden surges in grid demand, thereby actively contributing to grid stability (Altın & Sarp, 2020; Rao et al., 2025; UOS, n.d.; Yilmaz & Krein, 2012; Zhou & Li, 2015). Consequently, when determining optimal station locations, it is imperative to evaluate the network capacity in that area and the potential for integration with smart grid technologies as critical criteria. In this context, dynamic grid management technologies such as "smart charging" and V2G will be an integral part of future infrastructure. However, the effective planning of these complex systems necessitates, first and foremost, the resolution of a fundamental question: where should the stations be physically located? The present study endeavors to establish a critical "foundational layer" for these advanced grid integration goals. The selection of optimal locations, characterized by high demand density, was determined through the application of Fuzzy AHP and GIS methodologies. This strategic geographic foundation will serve as the foundational framework for future smart charging infrastructure and network optimization initiatives. Consequently, the present study concentrates on addressing the issue of location and demand density, which constitutes the initial and indispensable phase in the transition to more intricate and dynamic systems.

Beyond the technical and economic optimization of charging infrastructure, there is an emerging consensus that the planning of these systems must be fair and inclusive. The concept of “charging equity” aims to ensure that individuals from diverse socio-economic backgrounds and geographical locations have access to this technology by preventing the infrastructure from being concentrated exclusively in high-income and detached housing areas. The creation of accessible and affordable charging options in public spaces for apartment dwellers, tenants, and low-income communities without home charging capabilities is vital for the democratization of electrification (Carlton & Sultana, 2023; Esmaili et al., 2024; Li et al., 2022; Yu et al., 2025). Otherwise, there is a risk of “charging deserts” forming in certain areas; this situation could hinder the transition to electric vehicles for people living in these areas, thereby further deepening existing social inequalities (C. Jones, 2025; GSMP, 2021; Serrano et al., 2025; Zhou et al., 2022). Consequently, optimal selection models should encompass not only conventional demographic data, such as population density, but also more granular socio-economic indicators, including housing type, household income, and vehicle ownership, in their analyses. In this study, the concept of "charging equity" was addressed indirectly through the fundamental criteria used in the methodology, rather than directly through socio-economic data. Specifically, the 'C1-Population Density' criterion employed in the analysis *(see Methodology Section)* functions as a proxy for mitigating the risk of 'charging deserts' by aiming to serve the maximum number of users with the available infrastructure. Prioritizing high-population areas has the potential to increase access to public spaces for apartment dwellers who lack charging facilities in their residences. However, it is acknowledged that this approach has limitations and that integrating more granular socio-economic data, such as household income, property status, and housing type, into the model in future studies for an in-depth analysis of "charging equity" would further strengthen the social equity dimension of planning. Furthermore, the planning process must account for the spatial requirements dictated by the various charging technologies and usage scenarios. Level 2 (AC) charging units are particularly well-suited for “destination”-oriented locations, such as workplaces, residential parking lots, and shopping centers, where vehicles remain parked for extended periods due to their comparatively slower charging times. In contrast, DC fast charging (DCFC) stations should be strategically located along major highway corridors and urban thoroughfares to meet the need for rapid charging during short stops on extended journeys (Kłos & Sierpiński, 2023). The complexity of this multi-layered problem necessitates the use of advanced analytical tools to support decision-making processes.

The utilization of integrated models empowers decision-makers to identify the most strategically valuable locations by considering not only technically suitable sites but also socio-economic and environmental factors (Deb et al., 2018; Iravani, 2022; X. Liu, 2024). Consequently, this study underscores the pivotal role of optimal site selection for EV charging stations and underscores the necessity to formulate a data-driven, systematic, and replicable framework to address this intricate planning problem. The objective is to furnish a decision support instrument that will ensure the most efficient use of limited resources, promote charging equity, facilitate grid integration, and thus accelerate the spread of electric mobility, thereby contributing to the formation of smarter and more sustainable urban ecosystems. The primary objective of this study is to develop and implement a comprehensive and replicable framework for the optimal site selection of EV charging stations. This objective is accomplished by integrating a Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to address the inherent uncertainty and subjectivity in criteria weighting, in conjunction with Geographic Information Systems (GIS) to facilitate robust spatial analysis and synthesis. The objective of the study is to identify and prioritize suitable locations for new investments in EV charging stations. It offers a data-driven, strategic roadmap for local authorities and private sector stakeholders to effectively address the infrastructure gap and foster the transition to electric mobility.

2. Method and Data

2.1. Study Area Characteristics

The study area was specified as the central macroform boundaries of the Karesi and Altıeylül districts of Balıkesir Metropolitan Municipality (Figure 1). According to the Address-Based Population Registration Statistics of the Turkish Statistical Institute, the population of Altıeylül district is 185,351, and Karesi district is 190,427 (TÜİK, 2025a). According to the Motor Vehicle Statistics for Balıkesir Province, the number of electric vehicles increased by 1895% between 2020 and 2024 (TÜİK, 2025b). A total of 41 EV charging stations were identified within the main macroform that constitutes the study area, with a total of 49 slots (Google, 2025). There are approximately 41 vehicles per slot at existing charging stations, and considering the upward trend, it is possible to say that the infrastructure may be insufficient. In this regard, determining the optimal suitable areas within the relatively compact main macroform is important in terms of transportation planning and infrastructure investment phasing.

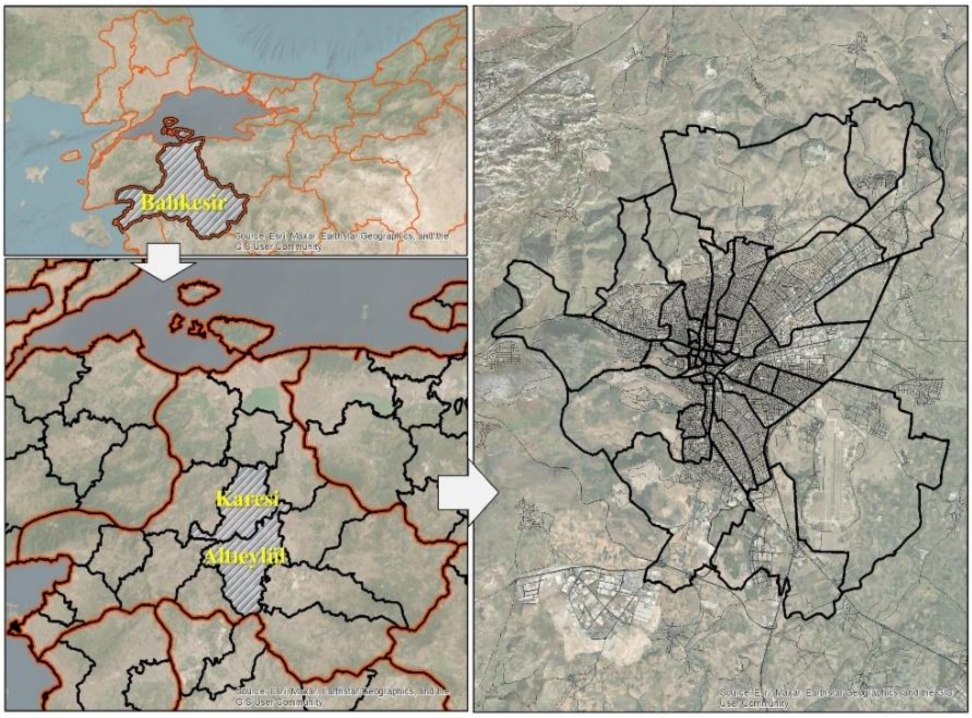

Figure 1. *Location of the study area (map source: current Google Earth satelite image)*

Table 1. *Statistics on motor vehicles registered for traffic by fuel type and year (compiled by the authors from TÜİK, 2025b)*

Years	Gasoline	Diesel	Hybrid	Electric	LPG
2020	10692	5241	105	339	543
2021	10830	4977	381	366	609
2022	15729	5168	403	1008	161
2023	31604	7205	879	4398	358
2024	37262	7178	2095	6672	311
Annual Change (%)	248.50	36.96	1895.24	1868.14	-42.73

2.2. Datasets and Method

The method followed to determine the most suitable areas within the macroform for the study is summarized in Figure 2. The steps followed in this context are described in detail in the following section.

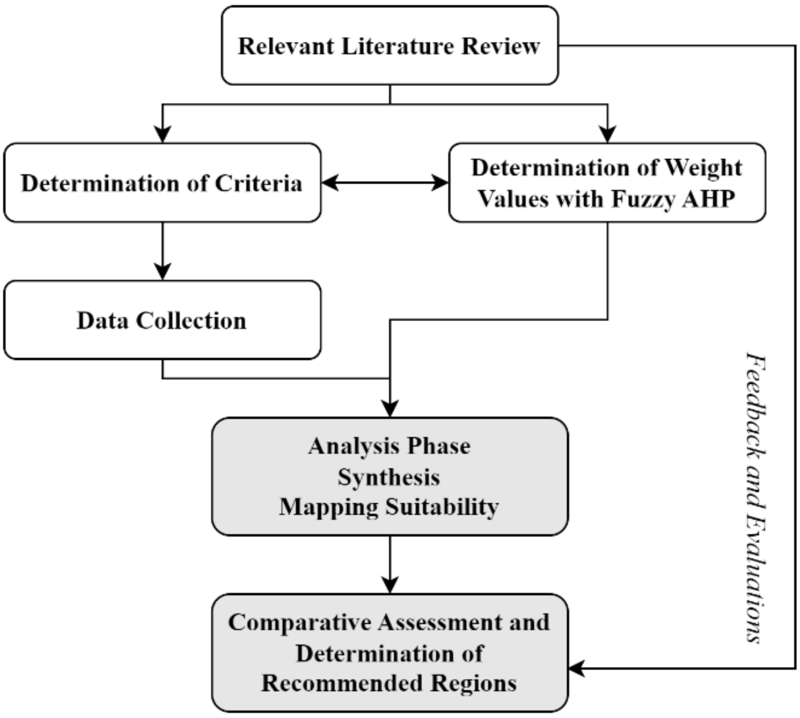

Figure 2. *Graphical summary of the study method (produced by the authors)*

[Phase-I]. Determination of Criteria and Data Collection: The main criterion in the legal regulations regarding EV charging stations is included in the Parking Regulation published in the Official Gazette No. 30340 dated February 22, 2018: *Article 6- (5) In newly constructed regional and general parking lots, as well as parking lots belonging to shopping malls, at least 10% of the parking spaces must be arranged in accordance with relevant standards to accommodate electric vehicles (including charging units). In shopping malls larger than 30,000 square meters, at least one charging unit must have fast-charging capacity in accordance with relevant standards, while in shopping malls larger than 70,000 square meters, at least two charging units must have such capacity. Authorities may decide to increase the number of electric vehicle parking spaces as needed*. In the context of the relevant legal regulation, it is seen that the main locations for EV charging stations are determined as public parking lots and mall parking lots, and it is possible to say that this will create a constraint in terms of urban accessibility. For this reason, the studies on this subject in the literature were analyzed in terms of methods and criteria (Table 2). The optimal positioning of charging stations not only increases user satisfaction but also balances the load on the grid and maximizes the return on investment. In this context, the criteria determined within the scope of the study in line with Table 2 and the relevant legislation are as follows: ***C1 - Population Density, C2 - Traffic Density, C3 - Slope, C4 - Distance to highways, C5 - Distance to transit stations, C6 - Distance to public service areas, C7 - Distance to existing parking areas, C8 - Distance to existing gas stations***. Explanations for the criteria are given below.

Table 2. *Literature reviewed in the process of determining the criteria (compiled by authors)*

#	Reference	Criteria	Method
1	(Bilgilioğlu, 2022)	Population Density, Slope, Proximity to Main Roads, Proximity to shopping malls, Proximity to Petrol Stations, Land Value Proximity to Official Institutions and Recreation Areas	GIS Analysis, Fuzzy AHP
2	(Farah et al., 2023)	Traffic convenience, Service capability, Construction cost, Distance of landsliderisk, Slope, Service radius	Survey Analysis
3	(Güler & Yomralıoğlu, 2020)	Population Density, Distance to Shopping Centers, Distance to Roads, Income, Distance to Transportation Stations, Distance to Gas Stations, Distance to Parking Lots, Distance to Green Areas, Slope, Land Values	GIS Analysis, Fuzzy AHP
4	(Alkan et al., 2023)	Slope, Proximity to forest areas, Proximity to water sources, Proximity to fault lines, Proximity to landslide areas, Distance to oil stations, Proximity to substations, Proximity to existing charging stations, Population density, Proximity to public areas, Proximity to main roads	GIS Analysis, AHP
5	(Asnaz & Özdemir, 2021)	Proximity to existing parking areas and substations	Fuzzy AHP, PROMETHEE, SMART
6	(Paçacı et al., 2025)	Proximity to fuel facilities, Proximity to shopping malls, building density, Slope, Proximity to existing charging stations, Proximity to public service areas, Proximity to main roads, Proximity to parking areas, Proximity to commercial/service areas	Fuzzy Logic DEMATEL, TOPSIS
7	(Erbaş et al., 2018)	Service area population, Proximity to junctions, Proximity to main roads, Proximity to the substation, Proximity to petrol station, Distance to other EVCS, Land Cost, Environmental/Geographical parameters	GIS Analysis, Fuzzy AHP
8	(Elomiya et al., 2024)	Proximity to metro entrances, Proximity to main roads, Proximity to parking areas, Population density, Proximity to fuel facilities, Proximity to trade-service-tourism areas, Existing infrastructure, Slope, Climatic features	Hybrid Delphi-GIS-MCDM-random forest model
9	(UAB, 2023)	Traffic volume, Natural disaster risks, Ground bearing capacity, Land size, Land price, Infrastructure status, Proximity to main roads, Proximity to parking and charging stations, Proximity to residential areas	PTV VISUM, Analysis based on algorithms

- **C1-Population Density:** Population density is a key indicator for predicting the spatial distribution of EV charging demand (Güler & Yomralıoğlu, 2020; UOS, n.d.). Highly populated residential areas have the highest demand for charging, especially for long-term (Level 2) charging. However, studies show that there is a positive correlation between population density and charging station utilization rates (Sanke, 2025; Tran et al., 2022). Therefore, prioritizing densely populated areas increases the utilization efficiency of the charging infrastructure, minimizes the risk of idle capacity and enables a wider user base to be served (Harshil & Nagababu, 2024).
- **C2-Traffic Density:** Traffic density or traffic flow volume is a major factor in the placement of DCFC stations, especially on main arteries and highways. Routes with high traffic flows offer access to a greater number of potential users for both urban mobility and intercity travel (Gulbahar et al., 2023; Lu et al., 2016). Stations located in areas of high traffic flow increased visibility for drivers, reduce “range anxiety” and strengthen the integrity of the network by meeting the need for en-route charging.

- **C3-Slope:** Topographical features, especially land slope, is a geographical constraint that directly affects the feasibility, cost and safety of a charging station project. However, the importance of slope as a criterion extends beyond mere construction feasibility. As highlighted by Yang et al. (2014), the additional energy required for a vehicle to overcome the change in potential energy (*mgh*) when moving uphill significantly increases the energy consumption of electric vehicles compared to flat roads. Therefore, keeping the slope low is not just a matter of convenience, but also a critical energy efficiency strategy for the entire transportation network. TS-12820 Fuel Stations-Safety rules and the Regulation on Facilities to be Built and Opened on the Side of Highways also define slope conditions for stations.
- **C4-Distance to highways:** The proximity of charging stations to highways, motorways and major transportation corridors is vital for the accessibility and efficiency of the network. Specific "alternative fuel corridors" are established on highways and primary roads to support alternative fuel types (Gulbahar et al., 2023; Hanig et al., 2025; JOET, n.d.).
- **C5-Distance to transit stations:** The integration of charging infrastructure with public transport hubs -such as metro, train stations, bus terminals- is a strategic approach to promoting sustainable urban mobility. Multimodal transport hubs encourage individuals to combine personal travel (for the first and last mile) with public transport. Charging points at transfer stations specifically serve "park-and-ride" use, both helping to reduce traffic congestion and making the use of electric vehicles more attractive (Hanak, 2025; JOET, n.d.; Shao, 2021).
- **C6-Distance to public service areas:** Public service areas (hospitals, schools, public buildings, recreational areas, etc.) are areas with dense human and vehicle traffic, and the proximity of charging stations to these areas enables stations to be used more effectively (Güler & Yomralıoğlu, 2020). Establishing charging stations close to public service areas also increases consumer spending in the businesses around these areas and contributes to micro-economic zones (Winn, 2024).
- **C7-Distance to existing parking areas:** Incorporating charging stations into existing parking lots is an extremely important criterion in terms of both cost-effectiveness and feasibility. Utilizing existing infrastructure without the need to acquire new land or undertake major civil works reduces deployment costs and time. However, parking lots are ideal environments for charging, as they are natural "waiting points" where vehicles are already parked for a certain period. This integration allows to optimize traffic load and land use, especially in dense urban areas (Clement-Nyns et al., 2010; Y.-W. Wang, 2008).
- **C8-Distance to existing gas stations:** Co-location of charging units with existing fuel stations is a strategic approach that capitalizes on drivers' established habits. Integrating EV charging stations into such facilities allows users to adopt new technology without changing their habits (He et al., 2016; Sadeghi-Barzani et al., 2014). In addition, the use of existing infrastructure provides both cost and logistical advantages.

The data is used within the scope of the criteria, and their sources are summarized in Table 3. All collected data were converted into 30x30 meter raster data in the WGS84-35N projection system. To compare analyses with different values and to prepare the result maps, normalization in the range of 1-2 was applied.

Table 3. *Datasets and sources used in the study (compiled by authors)*

Criteria	Data Source	Analysis Method
C1	Neighborhood-based population values (TÜİK, 2025a)	Population Density: People/km² ArcMap → Feature to Raster
C2	Traffic maps obtained from Google Maps were analyzed with the TrafficWiever plugin in QGIS software	The scale has been adjusted according to weekday and weekend traffic volumes ArcMap → Feature to Raster
C3	(USGS, n.d.)	ArcMap → Spatial Analyst → Slope
C4	(Open Street Map, n.d.)	ArcMap → Spatial Analyst → Euclidean Distance
C5	Locations have been collected from Google Maps via the Apify platform (Apify, n.d.)	
C6		
C7		
C8		

[Phase-II]. Determination of Weight Levels: Within the scope of the study, the fuzzy AHP method was used in parallel with the literature (see Table 2) to determine the weight levels for the criteria. Fuzzy Analytic Hierarchy Process (Fuzzy AHP) is an extension of the classical AHP method with fuzzy set theory to better model the uncertainty and ambiguity in decision makers' judgments (Chang, 1996; Y.-M. Wang et al., 2008). The main advantage of fuzzy AHP over classical AHP is that it allows for the mathematical modeling of uncertainty and imprecise information about importance levels.

van Laarhoven & Pedrycz (1983) suggested the use of triangular fuzzy numbers, stating that the classical AHP's requirement of sharp numerical values does not reflect the inherent uncertainty in decision makers' evaluations. The extended analysis method developed by Chang (1996) represented this uncertainty by the triad (l, m, u) and allowed the mathematical modeling of importance judgments. The use of linguistic variables is the second important advantage of fuzzy AHP. The concept of linguistic variables, introduced by (Zadeh, 1975) , enables decision-makers to use verbal expressions directly, such as “very important”, “important”, and “not important”. It has been stated that Fuzzy AHP yields more accurate results than classical methods in decision-making processes. Mikhailov (2003) developed the fuzzy preference programming approach and stated that synthesizing different expert opinions with fuzzy AHP yields more consistent results than the simple arithmetic mean approach of classical AHP. Fuzzy AHP's advantages in decision-making under risk and uncertainty are especially evident in dynamic and uncertain environments. Lee et al. (2008) state in their study that applying fuzzy AHP results in less decision regret than classical AHP. One of the most widely used fuzzy AHP methods in the literature is the triangular fuzzy number method. This method is frequently preferred due to its ease of calculation. The calculation stages of Fuzzy AHP according to this method are presented in Table 4 below (Moslem et al., 2022; Online Output, n.d.; Özdağoğlu & Özdağoğlu, 2007; Varshney et al., 2024). In determining the criteria weights, the comparison matrices of the studies in Table 2 and the comments on the criteria were analyzed, and an integrated approach was developed based on these evaluations.

Table 4. *Fuzzy AHP calculation steps (Online Output, n.d.)*

Step No	Process
1	**Establishing the hierarchical structure of the problem**
2	**Defining fuzzy numbers for performing the pair-wise comparisons** For a triangular fuzzy number Ã = (l, m, u) (l: Lower bound, m: Middle value, u: Upper bound) (1,1,1): Equal importance, (1,3,5): Slightly more important, (3,5,7): Strongly important, (5,7,9): Very strongly important, (7,9,9): Very highly significant Intermediate values: (1,2,3), (3,4,5), (5,6,7), (7,8,9)
3	**Creation the pair-wise comparison matrix Ã using fuzzy numbers** $\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix}$
4	**Calculation of fuzzy synthetic values (S_i)** $S_i = \sum_{j=1}^{n} \tilde{a}_{ij} \otimes [\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{a}_{ij}]^{-1}$

5	**Calculation of the relative magnitude of (S_i)**
	For two triangular fuzzy numbers $M_1=(l_1,m_1,u_1)$ and $M_2=(l_2,m_2,u_2)$,
	$V(M_2 \geq M_1)$ = {
	1, if $m_2 \geq m_1$
	0, if $l_1 \geq u_2$
	$(l_1 - u_2)/((m_2-u_2)-(m_1-l_1))$, otherwise
	}

6	**Calculation of the weights of criteria and alternatives in the double comparison matrix** $d'(A_i) = Min\, V(S_i \geq S_k) \quad k = 1,2,\dots,n, \qquad k \neq i$
7	**Calculation of the final weight vector** $W = (d(A_1), d(A_2), \dots, d(A_n))^T$
8	**Consistency checks** $CI = (\lambda_{max} - n) / (n - 1)$ $CR = CI / RI$ → if $CR \leq 0.10$, the result is consistent.

[Phase-III]. Analyzing and Synthesizing: Analyses were executed in accordance with the criteria specified in Phase 1, and final suitability maps were generated through the Weighted Sum tool of ArcMap software, employing the weight values calculated in Phase 2 (see Eq.1) (*C_i: normalized criterion each i map, W_i: weight coefficient assigned to this criterion)*.

$$Suiability\ Value = \sum_{i=1}^{n} (W_i\ x\ C_i) \tag{1}$$

3. Findings and Discussion

The findings obtained in accordance with the sequence presented in the methodology section and the discussion of the results are presented below.

3.1. Fuzzy AHP Findings and Assessments

In order to ascertain the relative importance of the criteria and to minimize subjectivity in the analysis, the weighting approaches of similar studies in the literature were examined (see Table 2). In this context, the comparison matrices in relevant studies and the rationale behind these matrices were analyzed in detail, and a synthesis evaluation was conducted. Consequently, a novel comparison matrix was formulated (Table 5) as a result of this synthesis assessment. The final weighting values assigned to each criterion are derived from the solution of this matrix, as presented in Table 6.

Table 5. *Synthesis comparison matrix developed within the scope of the study (calculated by authors)*

Criteria	C1	C2	C3	C4	C5	C6	C7	C8
C1	(1,1,1)	(1,3,5)	(5,7,9)	(1/2,1,2)	(1,2,3)	(1,2,3)	(1,2,3)	(1,2,3)
C2	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(1/3,1,3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
C3	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)
C4	(1/2,1,2)	(1/3,1,3)	(5,7,9)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
C5	(1/3,1/2,1)	(1,1,1)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
C6	(1/3,1/2,1)	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
C7	(1/3,1/2,1)	(1,1,1)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
C8	(1/3,1/2,1)	(1,1,1)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)

Table 6. *Weight levels of the criteria (calculated by authors)*

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	Mean (Weight Levels)
C1	0.223	0.326	0.184	0.223	0.196	0.194	0.196	0.196	**0.217**
C2	0.074	0.109	0.132	0.223	0.098	0.097	0.098	0.098	**0.116**
C3	0.032	0.022	0.026	0.032	0.02	0.032	0.02	0.02	**0.026**
C4	0.223	0.109	0.184	0.223	0.294	0.29	0.294	0.294	**0.239**
C5	0.112	0.109	0.132	0.074	0.098	0.097	0.098	0.098	**0.102**
C6	0.112	0.109	0.079	0.074	0.098	0.097	0.098	0.098	**0.096**
C7	0.112	0.109	0.132	0.074	0.098	0.097	0.098	0.098	**0.102**
C8	0.112	0.109	0.132	0.074	0.098	0.097	0.098	0.098	**0.102**

The determination of criterion weights indicates the relative importance of each criterion for the site selection phase. According to the evaluations, distance to highways (C4), population density (C1), and current traffic density (C2) were identified as the three most significant components. The remaining criteria (C5, C6, C7, and C8) exhibited relatively similar weight values, with the least significant component being topographic slope (C3). A consistency analysis was conducted to assess the consistency of the pairwise comparisons for the criteria. The consistency ratio, as determined by the calculations presented in Table 7, was found to be 0.01753. This value, which is below 0.10 according to the fuzzy AHP methodology stated by Liu et al. (2017), indicates that a very high level of consistency has been achieved. Consequently, this approach, which was developed through the synthesis of studies in literature, provides both a holistic perspective and a highly consistent determination of criterion weights.

Table 7. *Results of the consistency calculation (calculated by authors)*

Parameters	Formulation	Calculation	Result
λmax	$\Sigma\lambda_i$ / n	65.383 / 8	**8.1729**
CI	(λmax - n) / (n-1)	(8.173- 8) / (8- 1)	**0.0247**
RI	Criteria value (n=8)		**1.41**
CR	CI / RI	0.0247 / 1.41	**0.01753**
CR ≤ 0.10 ✓ - Consistent			

3.2. Criteria Analysis-Suitability Synthesis Findings and Assessments

The normalized analysis results presented in Figure 3 show the distribution levels of spatial factors critical for an EV charging station in the urban area. The analysis demonstrates the regions that exhibit notable potential for demand density and existing infrastructure integration. Maps C1 (population density) and C2 (traffic density) illustrate a pronounced concentration in the city center. As the extant literature emphasizes, the demand for charging stations is primarily driven by electric vehicle (EV) owners residing in densely populated residential areas and by vehicles traversing high-traffic flows (Ullah et al., 2024). In this context, central areas should be prioritized to meet daily charging needs. The C3 (Slope) map highlights the topography challenges, particularly in the western parts of the city. Yang et al. (2014) state that driving on sloping roads significantly increases the energy consumption of electric vehicles compared to flat roads. This effect is particularly pronounced as the slope angle of the uphill road increases, while the total electricity consumption also increases as the length of the uphill or downhill road increases. Additionally, during uphill travel, the electricity consumption of vehicles during the acceleration and constant speed phases increases, while the electricity recovered by regenerative braking decreases. The C4 (Distance to Highways) analysis reveals a substantial accumulation of scores within the urban center along the primary arteries. For users traveling long distances or requiring rapid charging, highway routes represent a significant strategic location. The European Union-AFID Regulation specifically calls for the establishment of alternative fuel stations along highway and primary routes (EU, 2014). Furthermore, a thorough examination of the maps, based on criteria C5 (Transfer Stations), C6 (Public Service Areas), C7 (Existing Parking Areas), and C8 (Existing Gas Stations), reveals additional findings. The concentration of these criteria in the eastern parts of the city, such as Paşa Alanı, Gümüşçeşme, Kuva-i Milliye, Hasan Basri Çağtay, Toygar and Plevne neighborhoods, suggests that these areas could serve as optimal locations for the implementation of EV charging infrastructure. Due to their proximity to both public services and existing transportation and parking infrastructure, these neighborhoods are potential hubs where charging stations can be integrated into the existing urban fabric with minimal cost and maximum efficiency. In conclusion, the findings indicate that the EV charging station location strategy should consider demand-driven factors (population and traffic density) as well as supply-side factors, such as existing infrastructure and geographical features. The eastern sides of the city have a more dominant role in demand management due to the advantages provided by the existing infrastructure, while the core center should be the main location of charging stations due to its high population and traffic density.

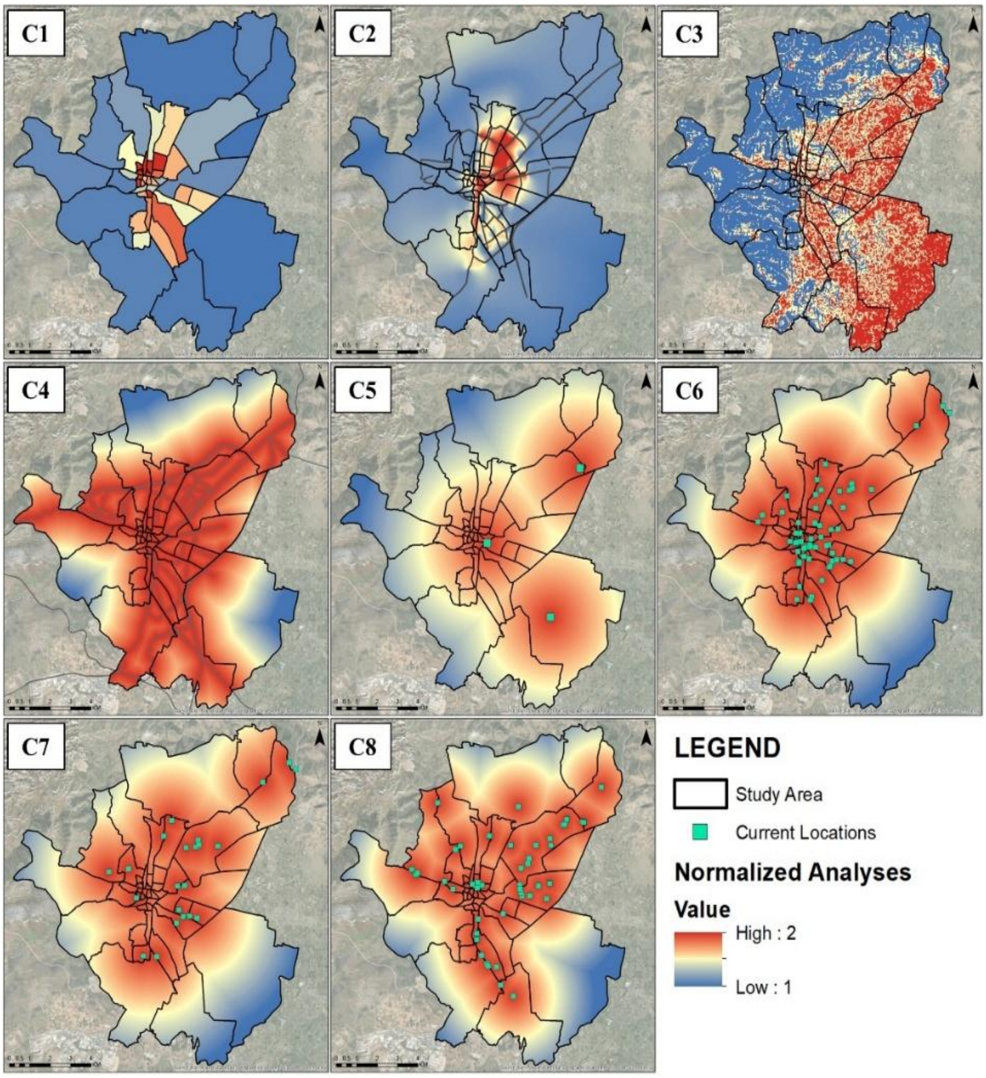

Figure 3. *Normalized analysis results (collective representation, produced by the authors)*

The synthesis, prepared according to the weight levels calculated in accordance with the fuzzy AHP method, is presented in Figure 4 and Table 8. The evaluation results indicate that the minimum value of the suitability analysis was calculated to be 1.07, with a maximum value of 1.92. The synthesis indicates that the central areas of the city exhibit the highest levels of suitability, as determined by the multi-criteria analysis. The neighborhood-based average suitability values presented in Table 8 provide quantitative evidence that corroborates this general spatial trend. As indicated by the data presented in the Table 8, centrally located neighborhoods such as Altıeylül (1.87967), Oruçgazi (1.85365), and Ege (1.81163) are identified as having the highest suitability values. Conversely, it has been observed that the suitability values undergo a gradual decline as distances from the urban center are increased. For instance, neighborhoods with low suitability values, such as Halalca (1.37897), Dinkçiler (1.39001), and Üçpınar (1.38075), tend to exhibit lower population densities, reduced traffic flow, and are situated farther from existing urban infrastructure. The location of charging stations within these neighborhoods should be considered as part of long-term urban expansion plans, rather than as a priority investment target at the initial stage. Despite their proximity to the city center, neighborhoods such as Gümüşçeşme (1.61027) and Paşa Alanı (1.63755) exhibit relatively lower suitability values compared to central neighborhoods. Consequently, the planning of the proposed charging stations should entail a comprehensive analysis that encompasses not only geographical proximity but also the socio-economic and infrastructural characteristics of each neighborhood. An analysis of existing EV charging stations reveals a concurrence with regions exhibiting high suitability, as determined by the synthesis result. However, it is possible to make different interpretations on a neighborhood basis. Neighborhoods such as Altıeylül (MSV: 1.87967), Oruçgazi (MSV: 1.85365), Yıldırım (MSV: 1.80660), and Atatürk (MSV: 1.78400) are noteworthy for their low EVCS numbers, despite demonstrating the highest degree of spatial suitability. Consequently, while these neighborhoods exhibit considerable promise, they are also characterized by a paucity of existing infrastructure. These neighborhoods can be regarded as the primary locations for new EV charging station investments, where limited resources will be allocated in the most efficient manner. Conversely, neighborhoods with medium-high Mean Suitability Values (MSV) but relatively high EVCS numbers, such as Paşa Alanı (MSV: 1.63755, EVCS: 9) and Plevne Neighborhood (MSV: 1.72344 , EVCS: 5), are regarded as areas where the potential is partially met by existing investments.The primary strategy in these areas should shift from the mere addition of new station points to the upgrading of existing infrastructure with the aim of increasing efficiency and user capacity. This approach should prioritize more specific interventions, such as upgrading existing Level 2 (AC) charging stations to DC fast charging (DCFC) to significantly reduce charging times, integrating battery storage units to manage sudden demand spikes and stabilizing the local grid, or implementing operational improvements (e.g., smart scheduling or reservation systems). The paucity of charging stations in neighborhoods with low MSV values, such as Halalca (MSV: 1.37897) and Dinkçiler (MSV: 1.39001), suggests the necessity of long-term planning in these areas. Consequently, it is determined that neighborhoods exhibiting high suitability and limited existing infrastructure, such as Altıeylül, Oruçgazi, Yıldırım, and Atatürk, should be prioritized for the effective implementation of EV charging infrastructure. According to the scenarios outlined in (UAB, 2023, p. 347), the electric vehicle (EV) charging infrastructure target for Balıkesir province is set at 154 charging slots by 2029 and 900 charging slots by 2053. These targets underscore the significance of strategic planning across various time horizons, including the short, medium, and long term. Achieving these targets and leveraging resources effectively necessitates conducting spatial location studies in this strategic direction.

Table 8. *Neighborhood-based synthesis evaluations (compiled by authors)*

N	MSV	EVCS	N	MSV	EVCS	N	MSV	EVCS
1. Gündoğan	1.78580	0	Çayırhisar	1.45031	4	Kayabey	1.76657	0
1. Oruçgazi	1.85365	0	Dinkçiler	1.39001	0	Kızpınar	1.55306	2
1. Sakarya	1.65225	1	Dumlupınar	1.65111	0	Kuvai-Milliye	1.49744	1
2. Gündoğan	1.69958	1	Ege	1.81163	0	Maltepe	1.65454	0
2. Oruçgazi	1.78298	0	Eski Kuyumcular	1.74309	0	Mirzabey	1.63347	0
2. Sakarya	1.47598	0	Gaziosmanpaşa	1.46429	5	Paşa Alanı	1.63755	9
Adnan Menderes	1.40914	0	Gümüşçeşme	1.61027	3	Plevne	1.72344	5
Akıncılar	1.74409	1	Hacı İlbey	1.69958	2	Sütlüce	1.67721	0
Ali Hikmet Paşa	1.79783	1	Hacı İsmail	1.79054	0	Toygar	1.70547	0
Altıeylül	1.87967	1	Halalca	1.37897	0	Üçpınar	1.38075	0
Atatürk	1.78400	0	Hasan Basri Çağtay	1.67233	0	Vicdaniye	1.80371	0
Aygören	1.75229	0	Hisariçi	1.78071	1	Yeni	1.42554	0
Ayşebacı	1.56173	0	Karaoğlan	1.75636	0	Yıldırım	1.80660	1
Bahçelievler	1.74283	1	Karesi	1.75662	1	Yıldız	1.66925	0
Çay	1.79613	0	Kasaplar	1.78377	1			

N: Neighborhood
MSV: Mean Suitability Value
EVCS: Current EC Charge Station Counts

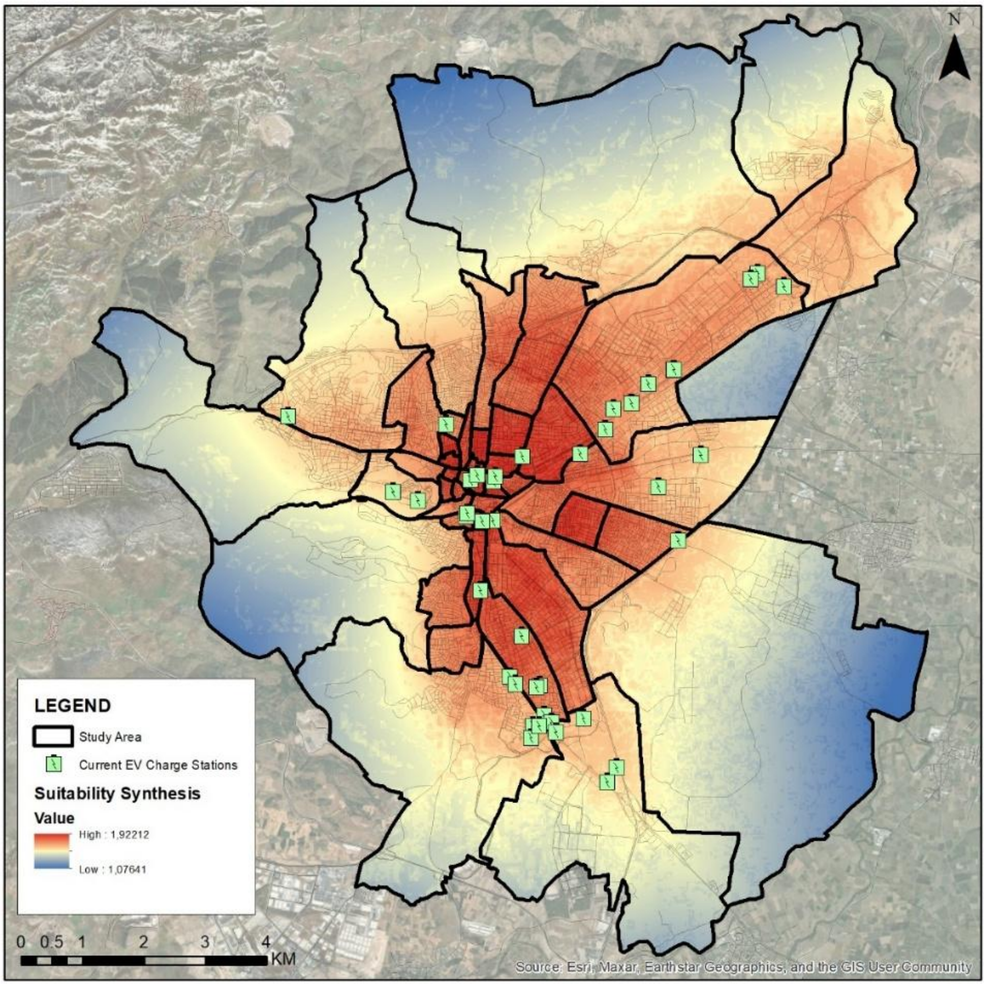

Figure 4. *Suitability synthesis for EV charging stations (produced by the authors)*

4. Conclusion and Discussion

The rapid dissemination of electric vehicle technology requires a paradigm shift in urban infrastructure planning. This study proposes a systematic approach to the optimal location of charging stations, tailored to the specific needs of urban areas, and deviating from the conventional logic of traditional gas stations. The study utilized a methodology based on the Fuzzy Analytic Hierarchy Process (FAHP) and Geographical Information Systems (GIS) to determine the optimal location of electric vehicle charging stations in the Karesi and Altıeylül districts of Balıkesir province. This integration allowed for the simultaneous analysis of multidimensional urban dynamics. The supply-demand imbalance, as evidenced by a remarkable 1895% increase in the number of electric vehicles in Balıkesir between 2020 and 2024, and the existing infrastructure's capacity of approximately 41 vehicles per slot, underscores the significance of this study. The methodological contribution of the study is the synthesis of different criteria in the literature to identify eight basic criteria and weigh these criteria with fuzzy AHP. The obtained consistency ratio of 0.01753 demonstrates the high reliability of the developed model. The findings indicate that proximity to main roads (0.239), population density (0.217), and traffic density (0.116) have the highest weight values. This suggests that accessibility and demand density are critical factors in charging station placement, in line with existing literature. A further contribution of the research is the finding that the location of charging stations is not only a technical optimization problem but also a complex decision process involving socio-economic, environmental, and behavioral factors. The developed model is expected to provide local governments with guidance on the most efficient use of their limited resources, while offering private sector investors a risk-minimizing planning tool. The methodological contributions of the Fuzzy AHP and GIS methods are evident in their capacity to manage subjectivity in the decision-making process. Fuzzy AHP is a system that solves complex problems by converting linguistic and uncertain judgments, such as "important" or "very important," into a mathematical model. GIS is a system that synthesizes these weights with geographic data layers. However, this approach also emphasizes the "user flexibility" dimension of location selection issues. The final suitability map presented in this study (see Figure 4) is the result of a specific weighting scenario (see Table 6) created based on a literature synthesis. The model itself possesses a flexible structure; for example, in a different stakeholder scenario where the local government prioritizes "charging equity" (see C1 parameter) or a private investor prioritizes "traffic density" (see C2 parameter), the model will produce a different suitability map. Consequently, the model presented should be regarded as a flexible decision support instrument capable of adapting to varying stakeholder priorities, as opposed to a singular "correct" outcome.

A notable limitation of this study is the inability to obtain detailed data on the urban electrical grid infrastructure. The availability of technical data, including the instantaneous capacities of transformers and the load limits of distribution lines, is not accessible through open/public sources. Consequently, while the model employs a comprehensive approach to identifying the most suitable geographic locations based on demand and accessibility, technical feasibility issues that are not addressed in this analysis include the question of whether these locations can be supported by the existing electricity grid. Consequently, the suitability map (see Figure 4) delineates high-priority investment areas; however, the ultimate determination regarding distribution will be made after a technical feasibility study and an evaluation of grid capacity. Moreover, the incorporation of innovative solutions such as charging stations integrated with renewable energy sources, V2G (Vehicle-to-Grid) technologies, and smart grid applications in spatial planning processes will facilitate the achievement of sustainable urban mobility goals. The findings provide information infrastructure not only for determining new station locations, but also for issues such as increasing the capacity of existing stations and technology transformation (such as switching from AC to DC fast charging). Comprehensive field research is needed to determine factors such as charging behavior of electric vehicle users, preferred locations and willingness to pay. In particular, the differences between the needs of users who do not have charging facilities at home, and the needs of commercial fleet operators necessitate segmented planning strategies. In future studies, it is recommended to extend the model to include dynamic demand projections and electricity grid constraints. Incorporating the infrastructure differences required by different charging technologies (Level 2 AC, DC fast charging) into the model, considering temporal demand fluctuations (daytime, weekday/weekend), and integrating the behavioral preferences of EV owners into the model through surveys will contribute to the development of a more comprehensive planning tool. This study indicates that policymakers should consider a more comprehensive EV infrastructure strategy that extends beyond current parking regulations. A critical factor that will accelerate the adoption of electric vehicles (EVs) is the expansion of charging stations beyond the confines of shopping malls and public parking lots. These stations require strategic placement to ensure accessibility within urban environments. In this context, it is recommended to establish a holistic legal framework that includes public-private sector cooperation models, incentive mechanisms, and mandatory infrastructure requirements. In summary, this study aims to contribute to the planning of future smart and sustainable cities by offering a model that integrates technical optimization with a deep understanding of the urban context, in line with urban sustainability objectives.

Ethics Committee Permission/Etik Kurul İzni:

Bu çalışma Etik Kurul Onayı gerektiren çalışma grubuna dahil değildir.

This study is not included in the study group that requires Ethics Committee Approval.

Conflict of Interest/ Çıkar Çatışması:

Yazarlar, kendileri ve/veya diğer üçüncü kişi ve kurumlarla çıkar çatışmasının olmadığını beyan eder.

The authors declare that they have no conflicting interest.

Authors' contribution/ Yazar katkısı:

Idea/Concept – G.K.,E.Ö.; Design and Design – M.K.Ö.,G.K.,E.Ö.,I.O; Auditing/Consultancy – M.K.Ö.,I.O; Sources – M.K.Ö.,I.O; Data Collection and/or Processing; M.K.Ö.,G.K.,E.Ö.; Analysis and/or Interpretation – M.K.Ö.,G.K.,E.Ö.,I.O; Literature Review - M.K.Ö.,G.K.,E.Ö.; Writing - M.K.Ö.,G.K.; Critical Review – M.K.Ö.,I.O.

Fikir/Kavram – G.K.,E.Ö.; Tasarım ve Dizayn – M.K.Ö.,G.K.,E.Ö.,I.O; Denetleme/Danışmanlık – M.K.Ö.,I.O; Kaynaklar – M.K.Ö.,I.O; Veri Toplama ve/veya İşleme – M.K.Ö.,G.K.,E.Ö.; Analiz ve/veya Yorum – M.K.Ö.,G.K.,E.Ö.,I.O; Literatür Taraması – M.K.Ö.,G.K.,E.Ö.; Yazı Yazan - M.K.Ö.,G.K.; Eleştirel İnceleme – M.K.Ö.,I.O;

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