Prioritizing Urban Policy Measures for Sustainable Electric Vehicle Using Fuzzy DAHP

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Abstract— **Urban transport systems require policy choices that reflect financial constraints and public response while addressing environmental pressures. The development of sustainable electric vehicle (EV) mobility in cities depends on selecting measures that align with municipal budgets and public expectations. This study applies the Fuzzy Delphi Analytical Hierarchy Process (FDAHP) to prioritize urban policy measures for sustainable electric mobility in Calabria, southern Italy. Expert judgments were collected through pairwise comparisons and converted into triangular fuzzy numbers to account for uncertainty in subjective evaluations. The aggregated fuzzy comparison matrix was then used to calculate and defuzzify the relative weights of six policy alternatives. The results indicate that Public Fleet Electrification and Free Urban Parking for EVs receive the highest priority, followed by Charging Infrastructure Investment. These findings suggest that, under constrained municipal budgets and local implementation challenges, policies directly manageable by urban authorities may offer more feasible pathways for promoting sustainable electric mobility.**

I. Introduction

Urban transport systems are under increasing pressure to reduce emissions while maintaining efficient mobility for growing urban populations. Road transport remains one of the largest sources of greenhouse gas emissions and local air pollutants in many cities [1], [2], [3]. In response, governments and municipalities have begun to promote electric vehicles (EVs) as a key pathway toward cleaner urban mobility. EV technology can significantly reduce tailpipe emissions and improve urban air quality. However, the transition toward electric mobility is not determined only by technological availability. It also depends on the policy choices made at the urban level. Municipal governments play a central role because they regulate parking, public transport fleets, local incentives, and infrastructure planning. Each of these policy areas can influence the pace and direction of EV adoption. Despite the environmental benefits associated with EVs, cities often face practical constraints when deciding how to promote them. Municipal budgets are limited, public acceptance can vary, and policy measures differ in their time requirements and implementation complexity. A policy that produces strong environmental benefits may also impose financial pressure on local governments. Conversely, a policy that is easy to implement may not generate meaningful environmental outcomes [4], [5], [6], [7]. For this reason, urban decision-makers must evaluate several criteria at the same time when designing EV policies. The challenge lies not only in identifying possible policy measures but also in determining which options should receive priority under real urban conditions.

Because electric mobility policy is still evolving in many regions, systematic evaluations of urban policy priorities remain relatively limited. Although several valuable studies have examined aspects of EV adoption and policy support, the body of research is still developing, and further investigation is needed to better understand how cities should prioritize electric mobility measures.

Bakker and Trip (2013) studied city-level policies to promote electric vehicle uptake using an expert workshop supported by a group decision room system. They classified measures into six groups and proposed two practical policy packages: one for frontrunner cities and one set of no-regret actions suitable for most cities [8]. Taefi et al., (2016) investigated that German EV policies mainly target urban passenger transport, while urban freight has different vehicle options, routing, and purchase drivers. They ranked 23 measures via a multi-criteria assessment using ratings from "policymakers" and "freight EV users" and found large gaps between the two groups. The study highlighted underestimated measures such as special legal rules and company-charging infrastructure, and pointed to options like zero-emission requirements in municipal tenders, class B licensing for freight EVs above 3.5 tons, and a long-term city toll [9]. Peng and Bai (2023) surveyed existing EV owners in Shanghai to examine how city incentives shaped purchase decisions and found local strategies were central to early adoption, shifting many first-time buyers from petrol cars to EVs. Measures such as free license plates and rush-hour highway access were cited as strong motivators. User feedback also pointed to barriers to scaling up, including poor conditions for private charger installation and weak

* This work was funded in part by the Master in Electric Mobility and Circular Economy (MEEC), financed by the "Ministry of University and Research" within the "Territorial Agreements for Higher Education" (CUP H52C23000090001). This work reflects only the authors' views and opinions; the Ministry for University and Research cannot be considered responsible for them.

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supporting services like infrastructure maintenance and a used-EV market [10]. Taamneh and Makahleh (2025) conducted a systematic review of 32 peer-reviewed studies (2004–2024) and grouped the main urban EV adoption drivers into five themes: economic, social, infrastructure, technology, and policy. They reported that policy levers such as financial incentives and stricter emissions rules are frequently emphasized, alongside affordability, charging-network expansion, and improvements in batteries and charging systems. The review also highlighted clear gaps between developed and emerging markets and called for tailored strategies and more research on rural and underrepresented groups [11]. Existing studies on electric mobility policies can be grouped into three main streams. The first stream focuses on policy incentives and regulatory measures supporting EV adoption, such as subsidies, parking benefits, access privileges, and charging support. The second stream examines user behavior and market acceptance, especially how citizens respond to economic, infrastructural, and service-related barriers. The third stream applies decision-support and multi-criteria methods to assess sustainable transport and mobility strategies. Taken together, these studies show that EV policy design involves not only technological and environmental considerations, but also behavioral, institutional, and financial dimensions.

While earlier studies have explored the drivers of electric vehicle adoption and the potential impacts of different policy incentives, fewer studies focus on how urban governments should prioritize policy measures when multiple practical constraints are present. In many cities, policy decisions are shaped by limited financial resources, administrative capacity, and public response to new regulations. These conditions make the evaluation of EV policies a multi-criteria decision problem. Environmental impact, implementation time, public acceptance, and financial feasibility must all be considered simultaneously. Conventional evaluation approaches often struggle to incorporate subjective judgments and uncertainty that arise when expert opinions are involved. Multi-criteria decision-making methods offer a structured way to address such problems. Among them, fuzzy-based approaches are useful because they allow expert assessments to be expressed in linguistic terms and then converted into quantitative values. This feature is particularly relevant when precise data are not available and decisions depend on professional experience and judgment. Even so, the application of fuzzy multi-criteria frameworks to urban EV policy prioritization remains relatively limited, especially in regions that face economic constraints and structural transport challenges.

This study seeks to address this gap by applying the Fuzzy Delphi Analytical Hierarchy Process (FDAHP) to evaluate and prioritize urban policy measures that support electric mobility. The analysis focuses on the region of Calabria in southern Italy, where economic limitations and infrastructure conditions shape local transport policy choices. Six policy alternatives are assessed from expert consultation. By combining expert knowledge with a structured decision framework, the study aims to identify which policy measures offer the most balanced outcomes for municipalities seeking to promote sustainable electric mobility.

II. Fuzzy Delphi Analytic Hierarchy Process (FDAHP)

In recent years, problem-solving has increasingly shifted toward the use of unconventional computational paradigms. Approaches such as neural architectures, meta-heuristic search strategies, data-driven learning techniques, and systems based on fuzzy sets—once regarded as specialized tools—are now widely applied in both research and industry. This change has largely been driven by the need to deal with uncertainty. In many real-world situations, data can be incomplete, noisy, or unstable, and the behavior of complex systems is not always easy to predict. Even so, numerous studies suggest that these approaches are still able to produce dependable models, carry out careful evaluations, and offer practical forecasts, even when the usual assumptions of certainty and linear relationships no longer apply [12], [13], [14], [15], [16], [17], [18]. Among these approaches, fuzzy logic stands out for its adaptability in handling modern, complex problems. As a form of multi-valued logic, it is particularly well suited to structuring and analyzing issues that involve multiple criteria. The fuzzy Delphi analytic hierarchy process (FDAHP) is one of the commonly applied fuzzy multi-criteria decision-making methods, especially in situations where information is limited or incomplete and expert judgment plays a central role. The main objective of this method is to combine expert opinions in order to achieve a well-founded and efficient group consensus [19], [20], [21]. The fuzzy Delphi method was originally introduced by Kaufman and Gupta as a development of the classical Delphi technique [22], [23]. Later, Liu and Chen (2007) outlined the procedural steps of the FDAHP framework as follows [24], [25].

Expert survey and construction of fuzzy numbers

At the outset, specialists in the relevant field are asked to provide their evaluations on the main subject. Their responses are then translated directly into fuzzy numbers. These values can be represented through either triangular or trapezoidal membership functions. In the present study, triangular fuzzy numbers (TFNs) ($\tilde{a}_{ij}$) are used. The corresponding membership function is defined in Eqs. (1) to (4) and depicted in Figure 1 [24], [25].

$$\tilde{a}_{ij} = (\alpha_{ij}, \delta_{ij}, \gamma_{ij}) \tag{1}$$

$$\alpha_{ij} = Min(\beta_{ijk}), k = 1, ..., n \tag{2}$$

$$\delta_{ij} = (\prod_{k=1}^{n} \beta_{ijk})^{\frac{1}{n}}, k = 1, ..., n \tag{3}$$

$$\gamma_{ij} = Max(\beta_{ijk}), k = 1, ..., n \tag{4}$$

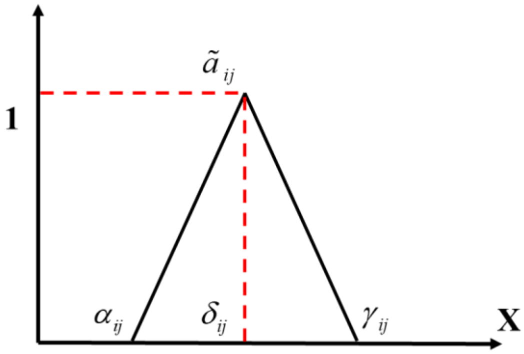

Figure 1. The triangular membership function applied in the fuzzy Delphi procedure.

Here, β_{ijk} expresses the Kth expert's judgment about the relative importance of the ith parameter compared to the jth parameter. α_{ij} and γ_{ij} represent the lower and upper limits of the experts' opinions, respectively, while δ_{ij} refers to the geometric median of those evaluations.

Forming the fuzzy pairwise comparison matrix

Based on the obtained fuzzy numbers, the fuzzy pairwise comparison matrix is constructed in accordance with Eq. 5 [24], [25].

$$\tilde{A} = \left[\tilde{a}_{ij}\right], \tag{5}$$

$$\tilde{a}_{ij} \times \tilde{a}_{ij} \approx 1,\ j = 1,2,3,........,n \quad \alpha_{ij}, \delta_{ij}, \gamma_{ij}$$

After constructing the comparison matrix, the relative fuzzy weight of each parameter ($\tilde{W}_i$) is calculated using Eqs. 6 and 7 [24], [25]. In this notation, "$\otimes$" represents the multiplication of fuzzy numbers, while "$\oplus$" denotes their addition. $\tilde{W}_i$ is a row vector that contains the fuzzy weight associated with the ith factor ($\tilde{W}_i = (w_1, w_2, ..., w_n)$, $(i = 1, 2, ..., n)$).

$$\tilde{Z}_i = \left[\tilde{a}_{ij} \otimes .... \otimes \tilde{a}_{in}\right]^{1/n} \tag{6}$$

$$\tilde{a}_1 \otimes \tilde{a}_2 = (\alpha_1 \times \alpha_2, \delta_1 \times \delta_2, \gamma_1 \times \gamma_2) \tag{7}$$

$$\tilde{W}_i = \tilde{Z}_i \otimes (\tilde{Z}_i \oplus .... \oplus \tilde{Z}_n) \tag{8}$$

Defuzzification of parameter weights

Finally, Eq. 8 is used to transform the fuzzy weights into crisp values, resulting in a single non-fuzzy weight for each parameter. The defuzzification process is performed using the geometric mean method [24], [25].

$$W_i = \left(\prod_{j=1}^{n} \tilde{W}_{ij}\right)^{1/n} \tag{9}$$

III. Case Study

Calabria is a region located in southern Italy, forming the southernmost part of the Italian peninsula. The region is characterized by a combination of coastal cities, mountainous terrain, and many small and medium-sized municipalities. Despite its natural and cultural resources, Calabria faces several structural challenges related to economic development and infrastructure. Compared with many northern Italian regions, Calabria has lower income levels and higher unemployment rates, which often limit public investment capacity and slow the modernization of transport systems [17]. Transport infrastructure and connectivity have long been important policy concerns in the region. Recent initiatives at the national and regional levels aim to modernize transport networks and promote more sustainable mobility solutions. Investments have been directed toward improving rail services, upgrading infrastructure, and supporting cleaner transport technologies.

These economic and infrastructural conditions make Calabria an appropriate case for examining how urban authorities can prioritize electric mobility policies when financial constraints, public acceptance, and implementation challenges must be considered simultaneously.

IV. Assessment of Electric Vehicle Policy Scenarios

Electric vehicles (EVs) have gained attention as cities search for ways to reduce emissions from urban transport. Conventional vehicles rely on fossil fuels and produce greenhouse gases and local air pollutants. Electric vehicles operate with electric motors and batteries, which remove tailpipe emissions during use. This feature makes them relevant for cities that face air quality problems and climate targets. Many national and local governments have begun to support the transition toward electric mobility [5], [26], [27]. Policy measures often include financial incentives, investment in charging infrastructure, and regulatory tools that encourage the use of low-emission vehicles. Public transport fleets and municipal service vehicles also receive attention in many urban plans. These policies influence both the speed of EV adoption and the long-term structure of urban transport systems. At the same time, policy design requires careful evaluation. Each measure has different economic costs, environmental effects, and levels of public acceptance. Some policies may encourage rapid adoption but require large public spending. Others may have smaller fiscal impacts but produce slower changes in vehicle markets. For this reason, a structured assessment of policy scenarios is required when cities consider strategies for electric mobility.

In this study, the assessment framework was developed through two stages. First, previous research on electric mobility policy was reviewed to identify a preliminary set of policy measures. Expert consultation was then used to refine this list. The participating experts had knowledge of electric mobility policy and familiarity with the conditions of the case study region. Through this process, six policy options were selected for the analysis. These options form the decision structure used in the FDAHP framework. The final set of alternatives is presented in Table 1. In this study, a single-level FDAHP structure was adopted. The six policy alternatives were directly compared by experts with respect to the overall goal of promoting sustainable electric mobility in the urban context of Calabria. Although dimensions such as environmental impact, financial feasibility, implementation complexity, and public acceptance guided the experts during their judgments, they were not modeled as separate criteria in the hierarchy. This simplified structure was selected because the objective of the study was to obtain an initial policy prioritization under limited data availability and within a context where expert knowledge plays a central role. Nevertheless, the absence of separately weighted criteria is acknowledged as a limitation, and future research should extend the framework by incorporating a full hierarchical structure including criteria and sub-criteria.

TABLE I. POLICY OPTIONS CONSIDERED FOR ELECTRIC MOBILITY DEVELOPMENT.

No.	Options
A1	Purchase Subsidies
A2	Tax Incentives
A3	Carbon Pricing
A4	Charging Infrastructure Investment
A5	Public Fleet Electrification
A6	Free Urban Parking for EVs

V. RESULTS AND DISCUSSION

This section presents the analytical results obtained from the application of the FDAHP framework. The analysis focuses on the relative importance of the selected policy alternatives for supporting electric mobility in the urban context of the case study region. The objective of this stage is to determine the priority of each policy option based on structured expert evaluation and fuzzy multi-criteria analysis.

A group of three university professors participated in the expert evaluation. All experts have academic experience in the field of electric vehicles and sustainable transport systems. They are also familiar with the socio-economic and transport conditions of the Calabria region. Their knowledge allowed them to evaluate the policy alternatives with attention to both technological aspects and local implementation conditions. Although the number of experts was limited, all participants were selected because of their direct academic experience in electric mobility, sustainable transport, and the regional transport conditions of Calabria. Therefore, the expert panel was intended to provide specialized judgment rather than statistical representativeness. This limitation is also acknowledged in the final section.

Each expert completed the pairwise comparison matrices required in the FDAHP method. The comparisons were carried out using Saaty's 1–9 scale, which is commonly applied in multi-criteria decision analysis [28]. This scale allows experts to express the relative importance of one option compared with another through numerical judgments. The individual matrices obtained from the three experts were then aggregated in order to construct a single comparison matrix for the analysis. The aggregation process reflects the collective opinion of the expert group. Table 2 presents the aggregated pairwise comparison matrix derived from the judgments of the three experts.

TABLE II. AGGREGATED FUZZY PAIRWISE COMPARISON MATRIX OBTAINED FROM EXPERT JUDGMENTS.

	A1	A2	A3	A4	A5	A6
A1	(1, 1, 1)	(0.2, 0.31, 0.5)	(0.33, 0.42, 0.5)	(0.14, 0.18, 0.25)	(0.11, 0.12, 0.14)	(0.12, 0.14, 0.16)
A2	(2, 3.2, 5)	(1, 1, 1)	(2, 2.3, 3)	(0.33, 0.44, 0.6)	(0.16, 0.17, 0.2)	(0.2, 0.23, 0.33)
A3	(2, 2.4, 3)	(0.33, 0.43, 0.5)	(1, 1, 1)	(0.25, 0.33, 0.5)	(0.14, 0.16, 0.17)	(0.16, 0.18, 0.25)
A4	(4, 5.2, 7)	(1.6, 2.2, 3)	(2, 3, 4)	(1, 1, 1)	(0.25, 0.31, 0.4)	(0.5, 0.63, 0.8)
A5	(7, 8.2, 9)	(5, 5.8, 7)	(6, 7, 8)	(2.5, 3.2, 4)	(1, 1, 1)	(1.5, 2, 2.5)
A6	(6, 7.1, 8)	(3, 4.3, 5)	(4, 5.4, 6)	(1.25, 1.5, 2)	(0.4, 0.5, 0.66)	(1, 1, 1)

After the construction of the fuzzy pairwise comparison matrix, the relative fuzzy weights of the policy alternatives are calculated. The calculation follows Eqs. (6) and (7) presented in the methodology section. These equations are applied to the final fuzzy comparison matrix in order to derive the fuzzy priority weights of the alternatives. The computation is performed for all six policy options, from A1 to A6. The resulting values represent the relative fuzzy importance of each alternative within the decision framework. In this step, $\tilde{W}_1$ to $\tilde{W}_6$ denote the fuzzy weights associated with the six policy options.

In the final stage of the analysis, the fuzzy weights are converted into crisp values. This process follows Eq. (8), which is used for the defuzzification of the fuzzy results. Through this step, a single numerical weight is obtained for each policy alternative. Table 3 reports the final weights and the resulting priority ranking of the policy options. In addition, Figure 2 illustrates the relative importance of the urban policy measures considered for the development of sustainable electric mobility.

TABLE III. FINAL WEIGHTS AND PRIORITY RANKING OF THE ELECTRIC MOBILITY POLICY OPTIONS.

No.	Policy Option	Relative Fuzzy Weight (Wi)	Final Weight	Rank
A1	Purchase Subsidies	(0.022, 0.030, 0.043)	0.030	6
A2	Tax Incentives	(0.067, 0.087, 0.138)	0.093	4
A3	Carbon Pricing	(0.038, 0.051, 0.081)	0.054	5
A4	Charging Infrastructure Investment	(0.111, 0.169, 0.277)	0.173	3
A5	Public Fleet Electrification	(0.273, 0.383, 0.539)	0.384	1
A6	Free Urban Parking for EVs	(0.185, 0.272, 0.387)	0.266	2

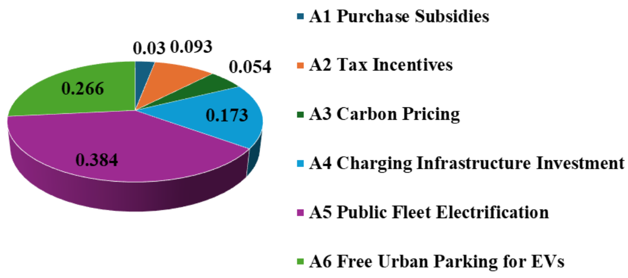

Figure 2. Relative importance (weights) of urban policy measures for sustainable electric mobility.

The results of the FDAHP analysis are presented in Table 3, and the relative weights are illustrated in Figure 2 for visual comparison. The ranking indicates clear differences in the perceived importance of the policy options. Public Fleet Electrification (A5) receives the highest weight, with a value of 0.384, and takes the first position among the six alternatives. Free Urban Parking for EVs (A6) follows in second place with a weight of 0.266. Charging Infrastructure Investment (A4) appears in the third position with a weight of 0.173. These three options form the group with the strongest priority in the analysis. The remaining policies receive lower scores. Tax Incentives (A2) holds the fourth rank with a weight of 0.093. Carbon Pricing (A3) is placed in the fifth position with a value of 0.054. Purchase Subsidies (A1) receives the smallest weight of 0.03 and is ranked last. The visual representation in Figure 2 helps illustrate the difference between the alternatives. The first two options show a clear gap from the other measures. This pattern suggests that the experts give more importance to policies that influence vehicle use in public systems and daily urban activity. Policies linked to financial incentives for private buyers receive lower attention in this evaluation. The ranking therefore highlights a preference for measures that cities can manage directly within the urban transport system.

The ranking can be explained in relation to the conditions of the Calabria region. The region includes many small and medium-sized cities. Public transport fleets and municipal service vehicles form an important part of daily mobility. Electrification of these fleets can produce visible environmental benefits in urban areas. Local authorities also have direct control over these vehicles. This control makes implementation more feasible compared with policies that depend on private vehicle markets. Free Urban Parking for EVs also receives a high position in the ranking. This measure is simple to apply and does not require complex administrative procedures. It can influence driver behavior in city centers where parking demand is high. Charging Infrastructure Investment takes the third rank. Charging stations remain necessary for the growth of electric mobility. However, installation requires financial resources and long planning procedures. The lower ranks of Purchase Subsidies and Carbon Pricing can also be understood in the local context. Calabria faces economic constraints and limited public budgets. Large subsidy programs can place pressure on municipal finances. Carbon pricing measures may require coordination at national or regional level. Local authorities have less direct influence over such instruments. The results therefore reflect the institutional and economic conditions of the case study region.

Several limitations must be acknowledged when interpreting the findings of this study. The FDAHP framework offers a structured method for evaluating policy priorities under uncertainty. The method can be applied to other urban contexts and case studies. The decision structure and evaluation process remain adaptable. However, the final ranking obtained in this research reflects the specific conditions of the Calabria region. Economic capacity, transport infrastructure, governance structure, and public behavior vary across cities and regions. These factors influence how experts evaluate policy options. The judgments used in the pairwise comparison matrices were provided by specialists familiar with the case study area. Their assessments reflect knowledge of local institutions and mobility patterns. In another region, experts may assign different levels of importance to the same policy measures. For example, cities with stronger financial resources may place greater emphasis on subsidies or large infrastructure programs. Dense metropolitan areas may also prioritize charging infrastructure in a different way. For this reason, the results presented in Table 3 should not be interpreted as a universal ranking for electric mobility policies. The findings represent a context-specific prioritization. Direct application of the same ranking in other regions may lead to misleading conclusions. Each urban area requires its own evaluation process that considers local economic, institutional, and mobility conditions.

VI. CONCLUSION

This study examined the prioritization of urban policy measures for the development of electric mobility through the application of the FDAHP. The approach provided a structured way to organize expert judgment and to evaluate policy alternatives under conditions of uncertainty. The analysis highlighted the role of municipal-level actions in shaping the transition toward cleaner urban transport systems. Measures that can be implemented directly by local authorities received stronger attention in the evaluation. These actions offer visible effects on urban mobility patterns and can be introduced within the operational structure of city transport systems. The results provide insight for urban decision makers who face financial limits and institutional constraints when planning policies for electric mobility. The proposed framework supports a transparent evaluation process and helps identify policy options that align with local conditions and governance capacity. Future research may expand this framework through the inclusion of additional criteria and a larger group of experts. Comparative studies across different cities or regions may also help identify how institutional, economic, and infrastructural conditions influence policy priorities. Further work can also integrate quantitative transport or environmental data with expert-based decision models to strengthen policy evaluation for sustainable urban mobility.

ACKNOWLEDGMENT

This work was funded in part by the Master in Electric Mobility and Circular Economy (MEEC), financed by the "Ministry of University and Research" within the "Territorial Agreements for Higher Education" (CUP H52C23000090001). This work reflects only the authors' views and opinions; the Ministry for University and Research cannot be considered responsible for them.

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