RANKING DEPLOYMENT STRATEGIES OF EV CHARGING INFRASTRUCTURE: A MODIFIED AHP WITH STAKEHOLDER PERSPECTIVE

Osman Öğünçlü[1], Seda Yanık[2]

Highlights

- A comprehensive criteria set has been identified as the goals of the electric vehicle charging infrastructure.
- A modified-AHP framework with multiple stakeholder perspective for ranking deployment strategies of electric vehicle charging infrastructure has been developed
- We propose that the deployment strategies selected without considering the stakeholder influences have limited applicability.

ABSTRACT

Electric vehicle (EV) adoption is an important initiative in preventing climate change. For the success of EVs, it is crucial to establish and operate an effective charging infrastructure. To achieve the desired goals of the charging infrastructure, multiple stakeholders play different roles and contribute in different ways. However, there is limited research on the relationships and priorities of the charging infrastructure goals from the stakeholders' perspectives. In this study, we present a comprehensive framework for the selection of charging infrastructure deployment strategies by identifying the priorities of the charging infrastructure goals from the stakeholders' perspectives. Charging infrastructure goals and alternative charging infrastructure deployment strategies are identified using an extensive literature review and expert interviews. The stakeholders of EV charging infrastructure have also been specified via literature review and theoretical aspects of the Stakeholder Theory. To the best of our knowledge, there are two studies for EV charging deployment strategy selection in the literature, yet do not incorporate the stakeholder viewpoints explicitly. From the stakeholders' unified perspective, we find that the prominent goals of the charging infrastructure are the integration, safety, digitalization and cost-effectiveness. In alignment with the priority goals, the two key charging infrastructure deployment strategies are ranked as: (i) supporting the improvement of electric distribution and smart grid systems and (ii) focusing on the development of smart charging systems.

[1] Istanbul Technical University, Industrial Engineering Department, Istanbul, Turkey, e-mail: ogunclu20@itu.edu.tr (ORCID: 0000-0002-0564-7757).

[2] Istanbul Technical University, Industrial Engineering Department, Istanbul, Turkey, sedayanik@itu.edu.tr (ORCID: 0000-0001-6260-7981).

Keywords (3-6): electric vehicles, charging infrastructure goals, deployment strategy selection, multi-stakeholder, AHP

1. Introduction

Effective planning and operation of the electric vehicle charging infrastructure is one of the key conditions for consumers in order to promote the widespread use of electric vehicles. Several current deployment strategies are being proposed to improve the charging infrastructure. However, implementing each of these deployment strategies in the short term is not feasible due to constraints such as cost and time. It is an important decision problem to determine which strategy should be prioritized to achieve the targeted goals of the charging infrastructure in the short term. In this study, we address the prioritization of charging infrastructure deployment strategies using AHP, a multi-criteria decision-making method.

Moreover, planning, establishment, and operation of electric vehicle charging infrastructure is a complex process. Electricity supply, electricity distribution, policies of government and local authority, technical specifications of electric vehicles and batteries, charging equipment, standards, software related to charging management, and information and communication technologies are some of the key components that make up the charging infrastructure. Each of these components is designed by various stakeholders with different goals and competencies. Therefore, it is important to consider the attitudes of different stakeholders in the development of the charging infrastructure. Considering this perspective, we propose a modified AHP approach that incorporates the stakeholder viewpoints for the prioritization of charging station development strategies in this study.

In this study, to determine which deployment strategies should be prioritized for the targeted charging infrastructure goals, we first examined how to measure the performance of the charging station infrastructure. We approach the performance of the charging infrastructure, which is a complex system, from a multi-criteria perspective. As a result of the literature review, it was determined that the charging infrastructure goals would be measured by the following criteria: (i) user experience, (ii) cost effectiveness, (iii) integration, (iv) digitization, (v) sustainability, (vi) resilience, and (vii) safety. Then, the eight stakeholders that affect the charging infrastructure are identified as: electric vehicle users, government and local authorities, charging station operators, charging equipment manufacturers and suppliers, e-mobility service providers, electricity distribution service providers, electric vehicle manufacturers, and universities/research institutions. Expert opinions were asked to evaluate the importance of the seven infrastructure goals according to each stakeholder. The responses are used then used to establish the criterion importance levels representing stakeholder views.

In the final step, five current alternative deployment strategies of CI are selected after reviewing sectoral/academic studies and are ranked using the modified AHP we propose.

As a result, we find that the two deployment strategies to be prioritized are Firstly; Supporting the improvement of distribution and smart grid systems. Secondly; Focusing on the development of smart charging systems. The approach presented in this study provides a multi-stakeholder and multi-criteria decision-making framework for planning. The results of this study will help in taking effective and efficient actions for the development of the charging infrastructure.

2. Literature Review

In the domain of EV charging station and infrastructure, we have reviewed the mcdm studies that have employed the AHP method in the last five years. We observe that most of these studies focus on the use of AHP for location/site selection (Elomiya et al., 2024; Yılmaz et al., 2023; Panah et al., 2022; Mahdy et al., 2022; Kaya et al., 2022; Khalife et al., 2022; Abdullah et al., 2022; Dang et al., 2021; Ghosh et al., 2021; Guler and Yomralıoglu, 2020; Karaşan et al., 2020; Kaya et al., 2020; Guler and Yomralıoglu., 2018). There are also a few studies that use AHP for smart reservation systems. (Gokcek et al., 2022; Sadreddini et al., 2021).

Parallel to our study, two studies address electric vehicle charging from a multi-dimensional system perspective as charging infrastructure in the literature. Anthopoulos ve Kolovou (2021) apply AHP using expert opinions for EV charging infrastructure deployment and operation respecting both the economic and the technical aspects for public charging stations. Additionally, their set of main criteria are defined with social, sustainable/environmental and political criteria. Their findings show that public EV charging stations are preferred to be located in private spaces ensuring their protection against vandalism within the urban areas.

Nanth et al. (2023) also proposes that deployment of adequate EV charging infrastructure is one of the most critical factors for seamless adoption of EVs. Their study presents a combined ranking of the key interventions using AHP. Each intervention is evaluated with the following criteria: number of EVs served, cost of EV charging, EV ecosystem benefits, implementation time. The values related to criteria are predicted quantitatively using a critical analysis of the interventions to be undertaken and the learnings have been utilized. Finally, the priority of the roll-out of the interventions are identified.

As summarized in this section, the literature of EV charging dominantly focus on location selection. Despite the importance of location in terms of accessibility from the consumer point of view and profitability from the service provider point of view, a holistic evaluation of the charging infrastructure as a system considering every dimension and component is important for a successful deployment. The literature, however, addressing the charging system as an infrastructure is limited. Moreover, the attitudes of the stakeholders influencing and depending on the charging infrastructure are not well studied. Among 18 studies reviewed in the last 5 years in this domain, ten studies mention the multiple stakeholder structure of the system but none of them explicitly propose an approach to include the views of the stakeholders. Hence, we include explicitly the attitudes of multiple stakeholders in the evaluations of the proposed MCDM framework we propose. In this study, we also identify the charging infrastructure as a complex system and evaluate it with an extensive set of criteria. The criteria set we consider include well studied charging infrastructure goals such as cost effectiveness but criteria such as resilience and integration which are realized to be important only recently.

3. Hypotheses/Objectives

Our overall objective in this study is to determine which deployment strategies should be prioritized for the targeted charging infrastructure goals incorporating the stakeholder perspectives. In our approach, we assume that the attitudes of different stakeholders are important for prioritizing the charging station deployment strategies in order to enhance the charging infrastructure. Based on our literature review and theoretical aspects of Stakeholder Theory, we identify eight stakeholders within the electric vehicle charging ecosystem. These stakeholders can be listed as follows:

(i) Electric Vehicle Users are individuals who own or actively and regularly use and charge electric vehicles.
(ii) Government and local authorities refer to the central government with nationwide authority and municipalities providing services at the regional level.
(iii) Charging station operators refer to organization that oversees the operation, management, administration, installation, and maintenance of EV charging stations.
(iv) Charging station manufacturers and suppliers are responsible for design and development, production, research and innovation and maintenance support for charging station operators. Suppliers provide manufacturers, materials including connector and cable
(v) E-Mobility Service Providers are organizations that deliver services enabling EV users to access and utilize charging infrastructure efficiently by providing EV users with access to a network of charging stations through mobile applications or other digital platforms.
(vi) Electricity distribution service providers are entities responsible for delivering electricity from the power grid to end users, including electric vehicle (EV) charging stations.
(vii) Electric vehicle manufacturers are another agent in the ecosystem by producing vehicles that align with the infrastructure and advancing the overall adoption of electric mobility. Their key roles include mainly vehicle development, battery innovation and integration between vehicles and charging networks
(viii) Universities and international organizations supports (EV) charging ecosystem through research and development, innovation, collaboration with other stakeholders and establishing global standards for charging connectors, communication protocols, and safety requirements.
In our approach, the viewpoints of the above stakeholders are unified from a multi-criteria perspective and the weights of the infrastructure goals are identified. Then, the deployment strategies are prioritized based on their impact on these goals. As a result of the literature review, we deduct that the charging infrastructure goals can be represented by the below criteria and their descriptions are given as follows:
G1 - User Experience: Overall satisfaction and ease of use that EV drivers encounter when interacting with charging stations and related services.
G2 - Cost Efficiency: Optimization of the financial aspects of deploying, operating, and maintaining charging systems while minimizing costs installation, maintenance, and operational costs for both providers and users.
G3 - Integration: Connection and coordination of charging networks including electrical grid and transportation networks.
G4 - Digitalization: Adoption of digital technologies to enhance the efficiency, functionality, and user experience of charging networks. It is supported by Interoperable, secure and fast digital platforms.
G5 - Sustainability: Minimization the environmental impact of charging operations while supporting the broader transition to a low-carbon, resource-efficient mobility ecosystem.
G6 - Resilience: Ability of the system to withstand, adapt to, and recover from disruptions, such as natural disasters, grid outages, cyberattacks, or other significant challenges. A resilient charging network ensures continuous service availability and reliability, even under adverse conditions.
G7 - Safety: The measures, protocols, and technologies implemented to protect users, equipment, and the environment during charging operations. It is critical for protection against accidents, electric shocks and electromagnetic fields.

4. Research Design/Methodology

Analytic Hierarchy Process (AHP) introduced by (Saaty,1980) is a mathematical framework designed to facilitate complex decision-making. The process starts with defining a hierarchical structure for the decision problem. At the highest level of the hierarchy is the main objective, while the intermediate levels outline the categories, criteria, or attributes used to evaluate progress toward achieving that objective. If needed, subcategories or sub-criteria can be incorporated below the main categories. At the bottom of the hierarchy, alternatives are introduced, linking them to all the subcategories, which are, in turn, connected to the main categories. Using a mathematical process, the information is synthesized to generate a prioritized ranking of the alternatives.

The primary objective of our study is to identify which goals gain greater significance in the development of electric vehicle (EV) charging infrastructure from the perspective of stakeholders. Subsequently, the study aims to systematically rank which deployment strategies can be implemented to address these goals effectively.

The research methodology of our study proposes a modified AHP with two main stages. In the first stage of the modified AHP, the process of determining the weights of the main criteria diverges from the traditional AHP method. In the classical AHP method, the importance levels of the main criteria weights are calculated through pairwise comparisons conducted by experts. However, in our study, experts are instead asked to assess the relative importance of the criteria based on the specified stakeholders' perspective. In our study the main criteria are defined as the EV charging infrastructure goals.

Data collection methods in this research are interviews and questionnaires conducted with key people who are experts in the EV charging domain. One of the key concepts of the model for determining the importance of goals from the point of view of different stakeholders is expressed by the Matrix of Stakeholder–Goal. This is called as MSG matrix. In our study, cells of the matrix express the intensity of the influence of any stakeholder in a row on any goal in a column using a 1–9 scale. The values in the cells represent the attitude of a stakeholder towards a given goal in the form of a positive sign since the all of the given goals are beneficial. Definition of the numerical scale is presented in Table 1:

Intensity	1	2	3	4	5	6	7	8	9
Definition	Absolutely Low	Very Low	Low	Slightly Low	Average	Slightly High	High	Very High	Absolutely Higy

Table 1: Stakeholder's influence on goal comparison scale

Let i represent the index for each stakeholder, where $i \in S$ and j represent the index for goal where $j \in G$. The expert evaluation score values, MSG_{ij}, are normalized as $NMSG_{\text{i}J}$ for each stakeholder i and goal j by dividing it to the total evaluation score of the corresponding stakeholder for each goal.

$$NMSG_{ij} = \frac{MSG_{ij}}{\sum_{J=1} MSG_{ij}} \; \forall \, i \in S, \forall \, j \in G, \tag{1}$$

Equation 3 measures the extent to which different actors are engaged within the system of interest,

$$R_j = \max_{i \in S} NMSG_{ij} - \min_{i \in S} NMSG_{ij} \quad \forall\, j \in G, \tag{2}$$

$$W_j = \frac{\sum_{i=1} NMSG_{ij}}{R_j} \;\forall\, j \in G, \tag{3}$$

where R_j is the range of the normalized score value of goal j with respect to stakeholders and W_j represents priority of goal j in the first level.

In the second stage of the modified AHP, the computed priorities of the goals are used to rank five current alternative deployment strategies of CI. Strategies of infrastructure deployment which we identified by extensive literature review and expert interviews are listed below:

- ST1. Mandatory implementation of electric vehicle charging infrastructure in buildings
- ST2. Supporting the improvement of distribution and smart grid systems
- ST3. Raising awareness on security vulnerabilities, sectoral opportunities and societal benefits.
- ST4. Focusing on the development of fast charging infrastructure
- ST5. Focusing on the development of smart charging systems

Follow-up interviews are conducted with the experts. In this stage, parallel to the classical AHP method, experts are asked to perform pairwise comparisons to evaluate how effective these strategies could be across seven objectives. The numerical scale used is provided in Table 2. Then, the priorities of strategies are calculated using classical AHP method. The consistencies of individual (or group) judgments are checked to ensure that the inconsistencies do not exceed the allowable threshold (Saaty, 2004).

Intensity	1	3	5	7	9	2,4,6,8
Definition	Equal importance	Moderately more important	Strongly more important	Very strongly more important	Extremely more important	Intermediary Values

Table 2: Pairwise comparison scale of strategies for AHP

5. Results/Model Analysis

To summarize the study described above within the framework of modified AHP, our three-tier hierarchical structure is illustrated in Figure 1.

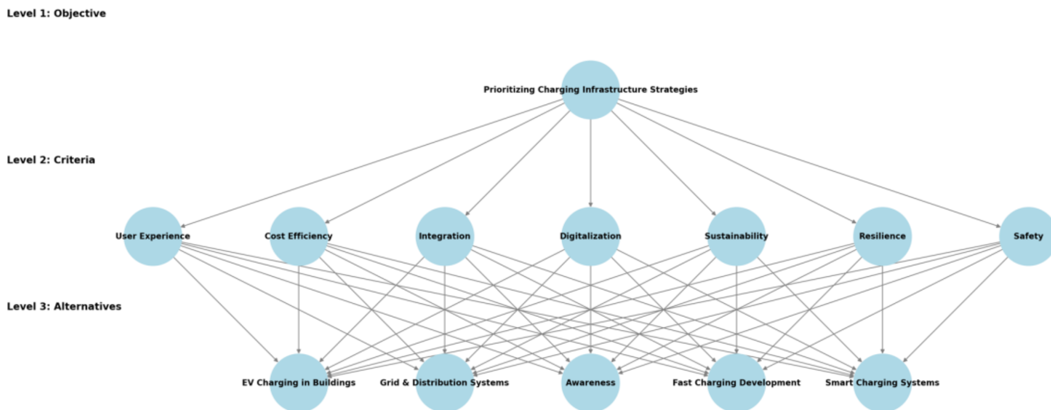

Figure 1: Hierarchy Diagram

The weights of the infrastructure criteria are determined by evaluating the impact of eight stakeholder classes on seven objectives separately. This evaluation is conducted by consulting the opinions of 15 experts representing various stakeholder classes, and the weights for each goal, to be used in the AHP, are calculated accordingly. The weights of the goals are presented in Table 3.

Goal	G1	G2	G3	G4	G5	G6	G7
Weight	0.09	0.13	0.24	0.14	0.15	0.1	0.15

Table 3: Weights of the goals

Using the weight values in Table 3 and the pairwise comparison of 5 alternatives with respect to 7 goals. Consistency ratio of pairwise comparisons for the goals “User Experience” and “Integration” are 16% and 11% respectively. Although Saaty suggested that the consistency ratio should not exceed 10% to ensure the reliability of decision-makers' assessments when using the AHP method. In such cases, particularly in emerging fields of real-life problems, a slightly higher consistency ratio may be considered acceptable. Nevertheless, in all pairwise comparisons conducted for the other goals, the consistency ratio remained below 10%.

Global weights and rankings of the 5 deployment strategies are calculated and presented in Table 4 below;

Strategy	ST1	ST2	ST3	ST4	G5
Score	0.18	0.26	0.16	0.17	0.23
Rank	3	1	5	4	2

Table 4: Global Scores and rankings of strategies

As seen in Table 4, strategies 2 and 5 are prioritized over others in achieving the goals related to EV charging infrastructure.

6. Conclusions

In conclusion, our study examined which strategies should be prioritized to achieve the goals of electric vehicle charging infrastructure development. As a result, Supporting the improvement of distribution and smart grid systems and focusing on the development of smart charging systems are the two strategies emerged as prominent. At second level, unlike the traditional approach of pairwise comparisons the importance of the goals, in our study was assessed by ensuring that each stakeholders' influence on the specified goals are explicitly incorporated. Within this framework, "Integration" goal which is defined as the connection and coordination of charging networks with electrical grid and transportation networks gained particular importance. By directly involving stakeholders in the process, a modified AHP structure was developed, yielding positive outcomes. Furthermore, the alignment between the priority objective identified at Level 1 and the prominent deployment strategies highlighted at Level 2 serves as evidence of the consistency and reliability of the evaluations conducted.

7. Limitations

During the expert evaluations conducted throughout the study, it was observed that the experts often had a limited understanding of the EV charging ecosystem, primarily considering it from the perspective of their own stakeholder class. Incorporating an evaluation of the interactions between stakeholders themselves could enhance the analysis in this regard. Additionally, increasing the number of interviewed experts to more effectively eliminate inconsistencies arising from pairwise comparisons is important for future studies.

8. Key References

- Anthopoulos, L., & Kolovou, P. (2021). A multi-criteria decision process for ev charging stations' deployment: Findings from greece. *Energies*, *14*(17), 5441.
- Nath, A., Rather, Z., Mitra, I., & Sahana, L. (2023). Multi-Criteria Approach for Identification and Ranking of Key Interventions for Seamless Adoption of Electric Vehicle Charging Infrastructure. *IEEE Transactions on Vehicular Technology*, *72*(7), 8697-8708.
- Saaty, T. L. (2004). Decision making—the analytic hierarchy and network processes (AHP/ANP). *Journal of systems science and systems engineering*, *13*, 1-35.