

Data-Driven Optimization of Electric Vehicle Charging Infrastructure: A Case Study of Sarajevo

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ABSTRACT

Globally, the use of electric vehicles is growing quickly as cities work to encourage sustainable transportation options and lower greenhouse gas emissions. However, the availability and optimal placement of charging infrastructure remain major challenges for many urban areas. In order to analyze and improve the infrastructure for charging electric vehicles in Sarajevo, Bosnia and Herzegovina, this study proposes a data-driven method. To determine the present distribution of charging stations and spot possible coverage gaps, the suggested approach combines geospatial analysis, publicly accessible datasets, and urban characteristics like population density and points of interest. The study identifies regions with low charging accessibility and makes data-supported recommendations for future infrastructure improvement using visualization and analytical tools. The findings show how data-driven decision-support tools may help energy companies, city planners, and policymakers create effective and sustainable EV charging networks.

General Terms

Algorithms, Spatial Analysis, Decision Support, Smart Cities

Keywords

Electric vehicles, charging stations, infrastructure optimization, spatial analysis, Sarajevo Canton, EV charging infrastructure

1. INTRODUCTION

For cities all across the world, the shift to environmentally friendly transportation has become a top priority. Due to their potential to lower greenhouse gas emissions, enhance air quality, and reduce our dependence on fossil fuels, electric vehicles (EVs) are becoming more widely acknowledged as a crucial part of this shift [4]. Through subsidies, laws, and investments in infrastructure for charging EVs, governments and policymakers around Europe are actively promoting EV adoption [4].

The availability and accessibility of charging infrastructure continues to be one of the biggest obstacles to broader EV adoption, despite the increased interest in electric mobility. "Range anxiety" is the term used to describe drivers' frequent worries about the availability of charging stations. These issues are especially relevant in urban areas where there are few charging outlets both in terms of quantity and location.

Sarajevo, the capital city of Bosnia and Herzegovina, is gradually experiencing growth in electric vehicle usage. The current infrastructure for charging, however, is still fairly small and distributed unevenly throughout the city. It is crucial to make sure that charging infrastructure is carefully placed to maximize accessibility and efficiency as the number of EV users rises.

A potential solution to this problem is data-driven spatial analysis. Geospatial data, demographic characteristics, and

urban activity patterns can be used to find the best places for new charging stations and identify areas with insufficient coverage.

This study offers an approach for determining priority zones for infrastructure growth and provides a data-driven analysis of Sarajevo's EV charging infrastructure. By offering insights that can help with more effective and sustainable EV charging network planning, the study hopes to assist policymakers and urban planners.

2. LITERATURE REVIEW

The problem of optimal placement of electric vehicle (EV) charging stations has been widely addressed in recent research. Various approaches have been proposed, ranging from optimization models to data-driven and machine learning techniques.

For instance, a study by He et al. (2013) focused on optimal charging station placement using flow-based models that consider traffic demand and transportation networks [1]. Their approach emphasizes minimizing travel distance and maximizing accessibility, but it relies heavily on traffic flow data, which may not always be available at a local level.

Similarly, Xi et al. (2013) proposed a location model for EV charging stations using simulation and optimization techniques [2]. Their work considers charging demand and grid constraints, but it is primarily designed for large-scale systems and lacks detailed spatial visualization.

More recent studies have incorporated machine learning techniques. For example, Wang et al. (2019) applied clustering algorithms such as K-means to identify areas with similar demand patterns for EV infrastructure [3]. While their approach effectively groups regions based on data characteristics, it does not directly integrate decision-support visualization tools for planners.

In addition, research reports by the International Energy Agency (IEA, 2023) highlight that uneven infrastructure distribution remains one of the main challenges for EV adoption globally [4]. These reports emphasize the importance of data-driven planning and accessibility metrics.

Unlike the aforementioned studies, this research focuses on a localized, data-driven analysis of Sarajevo Canton. It combines demographic data, existing infrastructure, and spatial analysis within a unified framework. Furthermore, this study extends beyond theoretical modeling by implementing an interactive web-based dashboard, enabling practical visualization and decision support. The integration of analysis and application represents a key distinction from existing work. This indicates a gap between theoretical planning models and localized decision-support implementations, which this study aims to address.

3. METHODOLOGY

This research applies a combined methodological approach that integrates quantitative analysis with analytical simulation of the spatial coverage of EV charging infrastructure. The main objective of the methodology is to evaluate the current distribution of EV charging stations in Sarajevo Canton and to estimate the number of additional charging stations required to achieve an optimal level of infrastructure accessibility.

The research method used in this study can be described as an analytical simulation of spatial infrastructure coverage. This method combines analytical modeling, descriptive statistics, and spatial analysis in order to quantify infrastructure availability and estimate future infrastructure requirements.

3.1 Data Collection

The study relies on multiple real-world sources obtained from public and institutional datasets. The Federal Statistical Office of Bosnia and Herzegovina provided important data, such as vehicle registration numbers and population statistics by municipality.

Publicly accessible websites like PlugShare, OpenStreetMap, and Google Maps were used to obtain further details about the locations and features of current EV charging stations [5], [6], [7]. Reports from energy suppliers like Elektroprivreda BiH were also examined for information about charging infrastructure operators.

These datasets serve as the basis for assessing the spatial distribution of charging infrastructure and examining the connection between the availability of charging stations and population density.

3.2 Data Integration

All collected data were integrated into a structured relational database implemented in MySQL. To support the analysis, a number of tables were created, such as the following: municipality, which contains demographic data such as population by municipality; charging station, which contains the location and features of current charging stations; evregistration, which contains annual statistics on registered electric vehicles; and evimport, which contains information about the import of electric vehicles.

The database structure makes it possible to search for and evaluate demographic and spatial information associated with the development of EV infrastructure in an effective way.

3.3 Analysis of Current Infrastructure Coverage

Evaluating the current state of electric vehicle charging infrastructure within Sarajevo Canton, a coverage ratio was calculated for each municipality, defined as the number of residents per available charging station.

One charging station per 4,000 residents was chosen as a benchmark infrastructure ratio for this investigation. This benchmark, which takes current EV adoption rates into account while aiming for a moderate level of accessibility, is based on planning assumptions that are frequently employed in early-stage EV infrastructure development [4].

Each city's infrastructure coverage level was determined using this benchmark, making it possible to identify locations with low charging availability. Underserved communities were those with a notably greater population density per charging station, suggesting a possible need for more infrastructure funding.

3.4 Simulation of Required Charging Infrastructure

A simulation model was created to calculate the number of extra charging stations required in each region in order to project future infrastructure requirements. The following formula was used to determine the necessary number of charging stations:

$$\text{Gap} = \text{TargetChargers} - \text{CurrentChargers}$$

The number of charging stations needed to reach the specified coverage benchmark is represented by TargetChargers. The number of charging stations that are currently available in the region is represented by CurrentChargers. Demographic information, the capacity of the current infrastructure, and possible charging spots like parking lots, business zones, and shopping malls are all included in the simulation.

3.5 Visualization of Results

The analytical results were presented through an interactive web-based dashboard developed using the React framework, with Leaflet employed for geospatial visualization. Interactive examination of the current charging infrastructure, coverage gaps, and data-driven recommendations for additional charging station locations is made possible by the dashboard. The system also incorporates decision-support features, such as budget-based optimization and scenario simulation, which enable users to evaluate the effects of various infrastructure planning approaches.

The visualization layer is essential for converting analytical results into useful insights, making interpretation easier, and assisting with data-driven decision-making.

3.6 Decision-Support Modules

In addition to spatial visualization, the developed application includes several decision-support modules designed to support EV infrastructure planning in Sarajevo Canton. These modules extend the analytical framework by allowing users to evaluate infrastructure gaps, simulate future demand conditions, and generate investment-oriented planning outputs.

The first module is the Coverage Gap Analysis module. It visualizes coverage areas around existing charging stations using an adjustable radius and identifies underserved zones where charging accessibility is limited. This enables a clearer understanding of spatial coverage and helps identify areas where new infrastructure may be required.

The second module is the Scenario Simulator. This module allows users to adjust planning parameters such as demand growth, EV adoption growth, capacity upgrades, and parking improvements. By modifying these parameters, users can observe how future changes may influence priority scores and infrastructure requirements. This feature supports what-if analysis and demonstrates the adaptability of the proposed framework.

The third module is the Budget Optimizer. This module allows users to define a total investment budget and estimated costs for new charging stations or infrastructure upgrades. Based on these inputs, the system generates a suggested investment plan and visualizes recommended actions on the map. This provides a practical planning tool for comparing infrastructure expansion options under limited financial resources.

These modules demonstrate that the proposed system is not limited to static visualization, but also provides interactive analytical support for decision-making.

3.7 Methodological Summary

The proposed methodology provides a structured framework for analyzing and optimizing EV charging infrastructure in Sarajevo Canton. By combining quantitative analysis, spatial modeling, simulation-based evaluation, and decision-support modules, the methodology enables a comprehensive assessment of current infrastructure conditions and future development needs.

A key advantage of this methodological approach is that it integrates multiple types of indicators, including demographic data, existing charging station distribution, infrastructure coverage, and potential demand-related factors. This allows the analysis to go beyond a simple count of charging stations and instead evaluate whether the current infrastructure is appropriately distributed in relation to population concentration and urban activity. The use of coverage gap analysis supports the identification of underserved areas, while clustering techniques provide additional insight into spatial patterns and groups of locations with similar characteristics. In addition, scenario-based and budget-oriented components make it possible to evaluate how future changes in EV adoption, demand growth, and investment constraints may influence infrastructure planning. Overall, the methodology supports both analytical evaluation and practical decision-making. It provides a scalable approach that can be updated with new data and adapted to other urban environments facing similar challenges in EV infrastructure development.

4. DATA DESCRIPTION

4.1 Population Data

The study uses a combination of demographic, infrastructural, and vehicle-related datasets to analyse the current state of electric vehicle charging infrastructure in Sarajevo Canton.

Population data were gathered from the Federal Statistical Office of Bosnia and Herzegovina. The dataset includes the total population for each municipality in Sarajevo Canton, including Centar, Novo Sarajevo, Novi Grad, Ilidža, Vogošća, Ilijaš, Hadžići, and Trnovo.

The ratio of population size to available charging stations is determined using these data, which also act as a main indicator for estimating infrastructure demand. This ratio serves as the foundation for determining underserved areas and evaluating infrastructure coverage.

4.2 Charging Infrastructure Data

Data on existing EV charging stations were collected from multiple publicly available sources, including PlugShare, OpenStreetMap, and Google Maps [5], [6], [7]. Geographic coordinates (latitude and longitude), site name and address, charging station type (AC/DC), and power rating (if available) are all included in the collection. To guarantee consistency and quality of geographical information, the dataset underwent data cleaning and deduplication methods due to the use of different data sources.

The resulting dataset is a crucial input for further spatial analysis and machine learning-based modeling of the best locations for charging stations. It offers an organized summary of the present spatial distribution of charging infrastructure throughout Sarajevo Canton.

4.3 Electric Vehicle Data

Data on registered electric vehicles were gathered from the Federal Statistical Office and related institutional sources. Annual statistics on the amount of registered electric and hybrid vehicles are included in the dataset. In order to examine patterns in EV adoption over time, data on electric car imports was also taken into account. These data are used for representing growth trends in EV adoption and act as a stand-in for estimating demand for charging infrastructure. Both the analytical evaluation of infrastructure requirements and the machine learning-based prioritizing of future charging station locations benefit greatly from the documented patterns.

4.4 Database Structure

All of the data was gathered, processed, and included into a MySQL relational database. The database contains several key tables: municipality, which stores population statistics by municipality; charging station, which stores location and technical characteristics of charging stations; evregistration, which stores yearly EV registration data; and evimport, which stores EV import data.

Demographic, infrastructure, and vehicle-related data can be efficiently integrated and cross-referenced because of the tables' logical connections based on shared spatial and temporal properties. In addition to allowing effective geographical and statistical indicator searching, aggregation, and analysis, the structured database forms the basis for further analytical processes and machine learning-based modeling of EV infrastructure design.

4.5 Data Limitations

The datasets provide a strong basis for analysis, although there are certain restrictions. Certain characteristics of charging stations, such as power rating and availability status, were not always accessible from all sources. Additionally, it was not possible to get real-time charging station usage data, which made it difficult to examine actual demand trends.

Additionally, small differences in spatial coverage could exist as a result of the integration of several data sources. Furthermore, the findings are specific to Sarajevo Canton and should be generalized to other regions with caution, since infrastructure availability, population density, and mobility patterns may differ across urban contexts. Considering these limitations, the available data are sufficient for analyzing infrastructure coverage and estimating future infrastructure requirements.

5. RESULTS

5.1 Current Infrastructure Coverage

The analysis provides insights into the current state of EV charging infrastructure in Sarajevo Canton and highlights areas with insufficient coverage.

The analysis reveals that the distribution of EV charging stations across regions in Sarajevo Canton is uneven. Infrastructure coverage is comparatively better in urban areas like Centar and Novo Sarajevo, which either reach or surpass the requirement of one charging station per 4,000 persons. Municipalities like Novi Grad and Ilidža, on the other hand, have substantial coverage gaps and far lower infrastructure levels than the norm. This imbalance is further confirmed through quantitative analysis of population-to-station ratios, which indicate that certain municipalities have substantially higher demand per charging station compared to others.

These results indicate significant geographical imbalances, with certain areas being underserved in terms of charging infrastructure due to the mismatch between current station distribution, population density, and expected demand.

5.2 Spatial Demand Analysis

A spatial demand analysis was conducted using demographic and geospatial data to identify areas with high potential demand for EV charging infrastructure. The results indicate the presence of concentrated demand zones, primarily in densely populated urban areas. These patterns are visualized through a heatmap, which highlights areas with higher expected demand

based on population density and spatial distribution of urban activity. This indicates that population density plays a key role in determining charging demand distribution.

5.3 Demand Heatmap Visualization

The demand heatmap provides a visual representation of areas with higher expected EV charging demand. High-demand zones are concentrated in densely populated urban regions and areas with increased commercial activity. This visualization supports the identification of priority locations for infrastructure expansion and confirms the results of the spatial demand analysis.

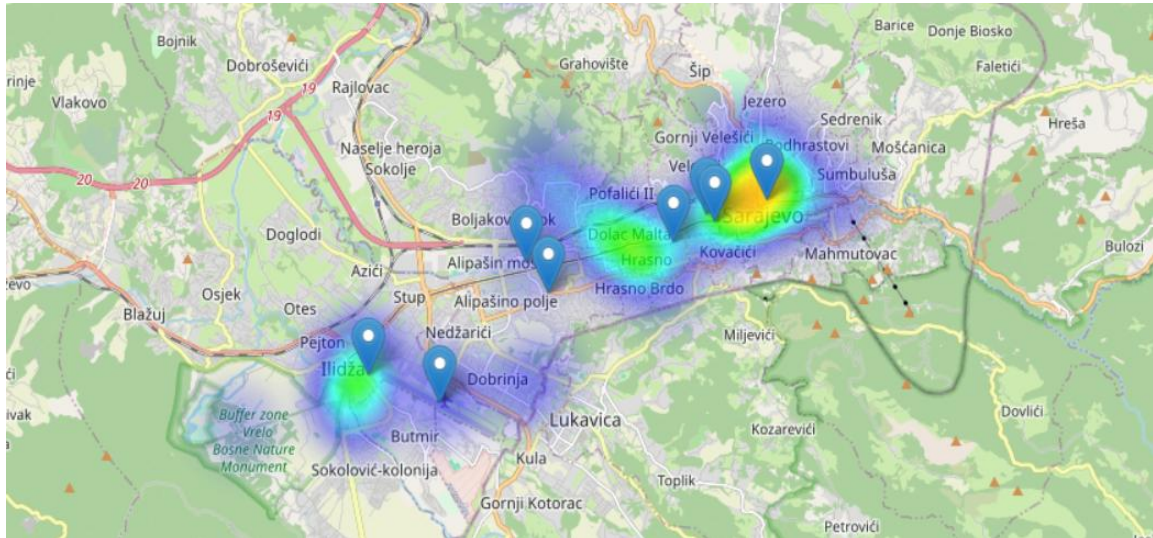


Fig 1: EV Charging Demand Heatmap in Sarajevo Canton

5.4 Clustering Analysis

To further analyze spatial patterns in infrastructure distribution, clustering techniques including K-means and DBSCAN were

applied. These methods enabled the identification of distinct clusters based on infrastructure density, demand indicators, and geographic characteristics.

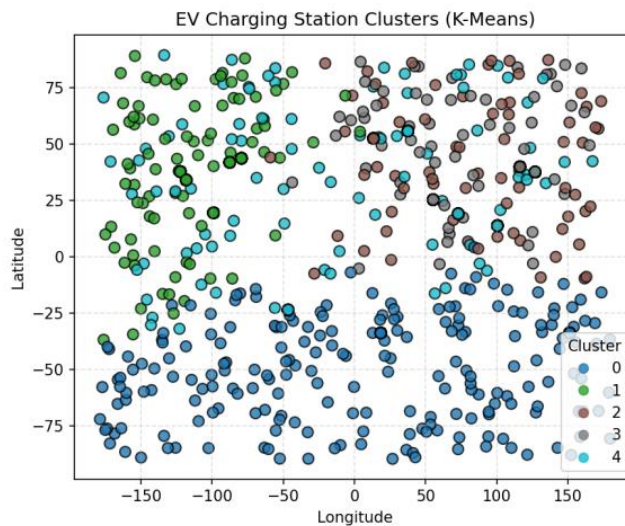


Fig 2: Clustering Results of Charging Stations using K-means Algorithm

The clustering results reveal groups of locations with similar characteristics, including areas with high demand but

insufficient infrastructure. These clusters were used as a basis for identifying priority zones for future development.

5.5 Recommended Zones for Infrastructure Expansion

A set of recommended zones for the installation of additional charging stations was generated based on the combined

analysis of demographic data, current infrastructure, and clustering results.

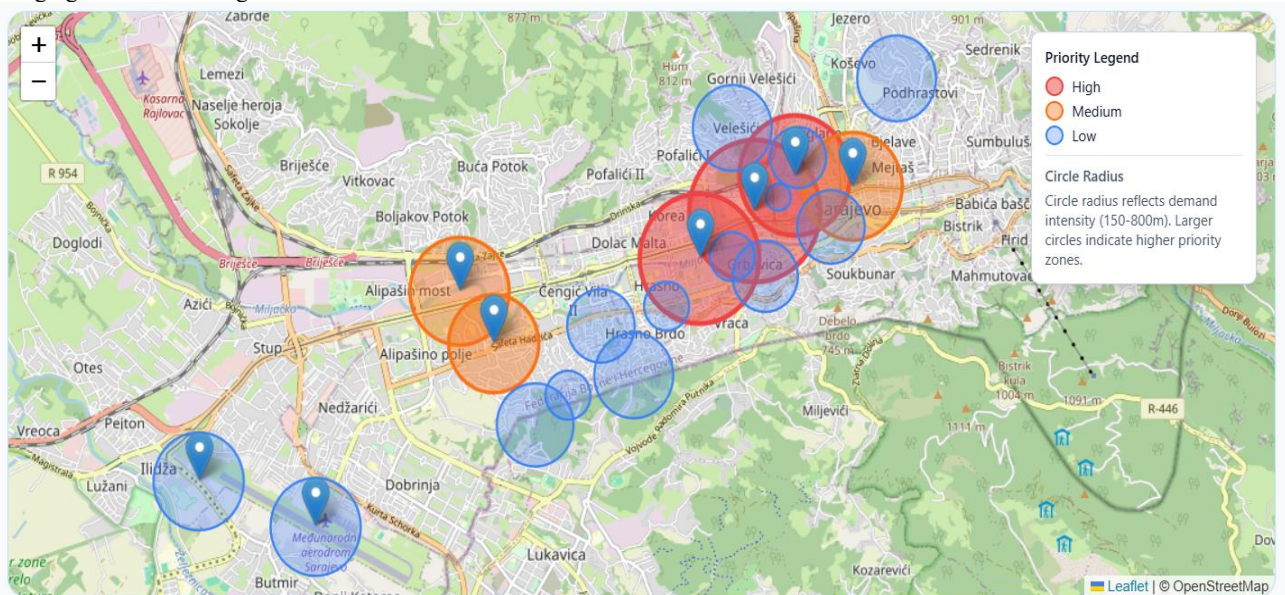


Fig 3: Recommended Charging Zones in Sarajevo Canton

5.6 Decision-Support Module Results

The decision-support modules provided additional insight into the planning of EV charging infrastructure in Sarajevo Canton. The Coverage Gap Analysis module enabled the identification of underserved areas by visualizing the spatial reach of existing charging stations. Areas located outside the defined coverage radius were interpreted as zones with weaker charging accessibility and higher potential need for future infrastructure development.

The Scenario Simulator demonstrated how changes in planning assumptions can influence infrastructure priorities. For example, increased EV adoption or demand growth leads to higher priority scores in densely populated areas and municipalities with limited existing charging infrastructure. This confirms that future infrastructure planning should remain flexible and should be updated as EV adoption increases.

The Budget Optimizer provided a practical perspective on infrastructure planning by linking recommended zones with investment constraints. By defining a total budget and estimated costs for new stations or upgrades, the module generates a prioritized investment plan. This supports more realistic decision-making because infrastructure expansion is evaluated not only from a spatial perspective, but also from a financial planning perspective. Overall, these modules strengthen the practical value of the proposed system by transforming analytical results into interactive planning scenarios that can support policymakers, urban planners, and infrastructure providers.

The recommended zones are primarily located in regions with high population density and low current infrastructure coverage. These areas represent priority locations for future investment and development of EV charging infrastructure. Current charging stations are also represented by the blue pins. This confirms that the proposed system can support both analytical evaluation and practical planning decisions under different infrastructure development assumptions.

5.7 Model Validation and Additional Analysis

Additional analytical procedures were conducted to evaluate the robustness of the proposed approach. These include feature importance analysis, sensitivity testing, and comparison of clustering methods. The results consistently indicate that population density and the spatial distribution of existing charging stations are the most influential factors in determining optimal locations for new charging infrastructure. In addition to the applied validation techniques, the proposed model was conceptually evaluated under different hypothetical scenarios.

These scenarios include variations in EV adoption rates and population growth, both of which directly influence the demand for charging infrastructure.

For example, an increase in EV adoption would lead to a higher concentration of demand in already densely populated urban areas, further intensifying the need for strategically located charging stations. Similarly, population growth and urban expansion would increase infrastructure pressure in municipalities that are already identified as underserved. Although these scenarios were not explicitly simulated within the system, they provide an additional level of evaluation and demonstrate the flexibility and applicability of the proposed approach in dynamic real-world conditions.

5.8 Summary of Findings

The results of this study clearly indicate that EV charging infrastructure in Sarajevo Canton is unevenly distributed, with significant disparities between central urban municipalities and peripheral regions. While areas such as Centar and Novo Sarajevo demonstrate relatively adequate coverage, other municipalities exhibit substantial infrastructure gaps.

The spatial demand analysis highlights that high-demand zones are primarily concentrated in densely populated urban corridors. These findings confirm that infrastructure deployment is not fully aligned with actual demand patterns,

indicating the need for more strategic planning. Furthermore, clustering techniques provided additional insights into spatial patterns, allowing the identification of groups of locations with similar infrastructure characteristics. These clusters proved useful in determining priority areas for future development.

Overall, the integration of spatial analysis, clustering methods, and simulation modeling offers a comprehensive framework for EV infrastructure planning. The findings demonstrate that data-driven approaches can significantly improve decision-making processes and support more efficient allocation of resources.

6. CONCLUSION

This research presents a comprehensive approach to analyzing and planning EV charging infrastructure within Sarajevo Canton. The study provides an assessment of the current state of EV charging availability by combining demographic data, existing infrastructure information, and spatial analytical methods. The findings indicate that the current charging infrastructure is unevenly distributed, with certain densely populated urban areas lacking sufficient charging capacity. By applying analytical techniques and simulation-based modeling, the study identifies priority zones where additional charging stations are needed to support a more accessible and balanced infrastructure network.

Clustering techniques such as DBSCAN and K-means were applied to group locations according to infrastructure characteristics and demand-related indicators. These techniques supported a more structured interpretation of spatial patterns and helped identify areas with similar infrastructure needs. The results were presented through an interactive web-based dashboard, enabling users to explore infrastructure coverage, demand distribution, and recommended expansion zones.

A key practical contribution of this research is the implementation of the analytical framework within a web-based decision-support application. The application includes

coverage gap analysis, scenario simulation, and budget optimization modules, allowing users to explore different planning conditions and investment strategies. This strengthens the practical applicability of the research and demonstrates how software-based tools can support data-driven infrastructure planning.

The proposed methodology offers a scalable and adaptable framework that can be applied to other regions facing similar challenges in EV infrastructure planning. Future work may include the integration of real-time charging usage data, traffic patterns, and more advanced machine learning models to further improve prediction accuracy and planning efficiency. Overall, this research bridges the gap between theoretical EV infrastructure planning models and practical, data-driven implementation in real-world urban environments.

7. REFERENCES

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