Optimizing Electric Vehicle Charging Infrastructures: A Microscopic Review

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Abstract

Electric mobility represents a paradigm shift toward a more energy-efficient, low-carbon, and environmentally friendly mode of transport. Choosing the optimal locations for Electric Vehicle (EV) charging stations is critical for EV adoption. Since EVs emit fewer greenhouse gases than internal combustion engines, their adoption is considered to be more environmentally friendly. Numerous factors affect the location-allocation problem for EV public charging stations, including understanding demand, assessing needs, identifying possible locations, and selecting an optimization model for facility location. This study conducts a literature review on the optimization of electric vehicle charging stations. Conclusions and recommendations for future research were extracted and documented.

Keywords
Electric Vehicle, Location Optimization, Charging Stations, Transportation.

1. Introduction
Over the last decade, climate change and its continued growth have been among the most investigated and debated issues (Kucukvar et al., 2021). Governments have responded by enacting a variety of policies and regulations aimed at reducing greenhouse gas emissions. Recently, gasoline-powered automobiles were the second largest source of greenhouse gases, trailing only factories and power plants (Shehab et al., 2021). Thus, when powered by natural gas or renewable energy, electric vehicles (EVs) are a viable alternative to internal combustion engine vehicles because they emit less pollution and consume less energy (Al-Buenain et al., 2021). Around 2010, several countries saw a surge in electric vehicle adoption. However, market penetration of EVs varies by country due to a variety of factors including government policies, incentives, and other socioeconomic factors. Countries, notably China, the United States of America, and Europe, are implementing strategies to promote electric vehicles. As a result, global EV sales exceeded 3 million vehicles in 2017 and are expected to continue growing; Norway has the highest percentage of electric vehicles on the road, and more than 400,000 charging stations were available globally in 2017. (Nicholas & Hall, 2018). These markets are not yet mature, and additional development of policies, battery and charging technologies, and charging infrastructure is required. Other EV markets, particularly in the Middle East (Qatar), are in their infancy, necessitating the planning of public charging infrastructure. Qatar is considered one of the most polluting countries due to its small population and extensive industrial activity (when measured per capita). Qatar's government is aware of pollution's dangers and has launched several new environmental initiatives. Qatar will host the FIFA World Cup 2022 in November 2022, and to demonstrate its environmental sensitivity, Qatar has committed to hosting the world's first carbon-neutral World Cup (Kucukvar et al., 2021; Spanos et al., 2021).

Home charging ownership is a significant factor in determining the design and location of charging stations. In countries (regions) with a low rate of home charging ownership, it is critical to deploy public chargers to encourage use, as this will become a necessity and the primary mode of charging. Whereas providing public chargers provides convenience and assurance to users in countries with a high rate of home charging ownership, providing public chargers provides convenience and assurance to users as the second option after home charging. 30% of EV drivers in Beijing rely entirely on public charging networks due to a lack of home chargers (Pan et al., 2020). In countries such as Norway, Germany, and the United States, reliance on public charging is lower, as the majority of users have access to home charging. Public chargers must be strategically located and planned to effectively capture demand. Models of facility location problems have been applied in a variety of domains, including emergency response, fire, medical, educational, waste management, and hospitals; the objectives of the various models vary according to the purpose. For instance, when applying the facility location model to EV public charging stations, accessibility is a critical factor. At the public level, slow chargers take 30 minutes to two hours to charge an EV; as a result, customers are less likely to wait this long in an inconvenient location. This section will provide background information on electric vehicles and their charging modes. Additionally, it reviews the research on EVs to gain a better understanding of the factors affecting uptake and the need for charging. Finally, it reviews the literature on EV charging station allocation studies to gain a better understanding of potential locations, demand estimation, and location allocation models.

2. Electric Vehicle and Charging level

This section discusses the various types of electric vehicles and charging modes available to foster a common understanding. There are three types of electric vehicles: hybrid (HEV), plug-in hybrid (PHEV), and plug-in electric vehicle (PEV), which is occasionally referred to as a battery electric vehicle (BEV). In addition to the internal combustion engine, the hybrid electric vehicle is equipped with a battery. The battery can be recharged only while the vehicle is moving, and the generated energy is used to power the vehicle. The advantage of an HEV is that it increases the vehicle's range and efficiency. The PHEV is equipped with a battery that can be recharged at stations or homes, as well as a fuel tank. This option provides drivers with greater flexibility. However, the disadvantages include the high cost and limited storage space required by the battery and electric motor. The BEV's sole source of energy is the battery. In current EV markets, the majority of users of public chargers are BEVs. As a result, throughout the remainder of this paper, BEV will be abbreviated as EV. BEVs and HEVs are expected to dominate the EV market, and PHEVs may become obsolete (Rietmann & Lieven, 2019).

The time required to charge an EV is significantly longer than the time required to refuel at a gas station. Charging can take 30 minutes or more than 8 hours, depending on the charging mode and equipment (Onat et al., 2021). This is one of the reasons why the requirements for EV charging stations must be evaluated differently than those for gasoline stations. Various types of chargers are available for charging the EV. The International Electrotechnical Commission defines four charging modes (IEC). The primary distinction between the modes is the ability to control charging power and safety level. Modes 1 through 4 are as follows: mode 1, mode 2, mode 3, and mode 4. Modes 1-3 operate on alternating currents and are slow level 1 and level 2 chargers that are commonly used at home, work, and public locations. Mode 4 is a direct current fast charger capable of delivering 50 kW to 350 kW. (Nicholas & Hall, 2018). Figure 1 illustrates the various charging methods available.

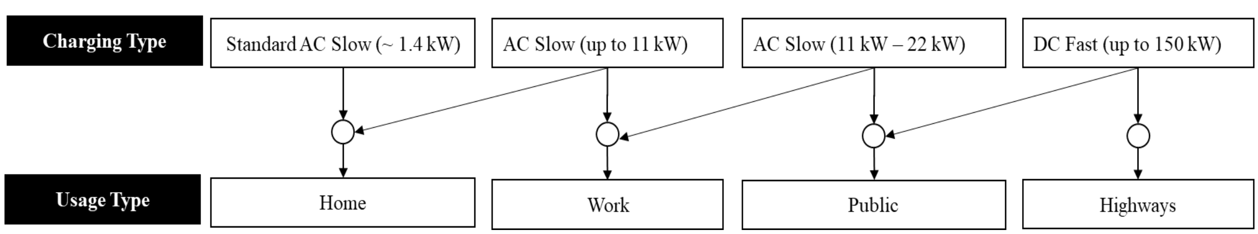

Figure 1. Existing EV charging types

3. Factors affecting EV uptake

Several factors influence electric vehicle adoption in different regions; these can be classified as buyer characteristics, enabling environment, and external factors. This section will discuss who is more likely to be an early adopter of EVs, the enabling environment in terms of policies, infrastructure, population density, and energy prices, as well as some other known influencing factors. Numerous studies have been conducted to ascertain the characteristics of electric vehicle purchasers. For instance, Axsen et al. (2016) conducted an in-depth survey in Canada and discovered that respondents who own multiple vehicles are more likely to be EV adopters. Similarly, respondents who own an EV earn more money and have a higher level of education, live in a single-family detached house, and have access to home charging. Additionally, early EV adopters were likely to be middle-aged men. Jakobsson et al. (2016) analyzed GPS travel data from single- and multi-vehicle households in Germany and Sweden to better understand their driving patterns. They conclude that the second car is better suited to replacing an affordable EV with a small battery because it travels shorter distances.

Other researchers in other countries report similar findings. Morton et al. (2018) analyzed population characteristics in various regions of the United Kingdom with high EV sales. They report that regions with a higher per capita income, a higher level of education, and a higher employment status are more likely to adopt electric vehicles than others. Brückmann et al., (2021) analyzed the individual and spatial characteristics of actual EV buyers in Switzerland using the revealed preference approach. The study shed light on early adopters in regions with lax EV policies. Switzerland does not have as robust a policy as countries such as Germany or the United Kingdom, where, for example, 4000 € purchase premia are available. Their study found that EV adopters have a higher income and education level, are more likely to be multi-car households and are owners of standalone houses. Additionally, the enabling environment is critical. It is policies such as regulations and incentives, the availability of charging infrastructure, and the range, reliability, and cost of electric vehicles that determine their viability (Higueras-Castillo et al., 2021). According to studies, policies that increase the market share of EVs are effective and, when canceled, resulting in a decline in sales (Wang et al., 2019). Yao et al. (2020) used econometric models to examine the effect of various policies on EV sales in 13 countries, including subsidies, fee waivers, and others. Subsidies, waivers, and mandates all had a positive effect on EV sales volume. The presence of public chargers was found to be extremely effective, with a 1% increase in the density of slow public chargers resulting in a 0.7 percent increase in EV uptake.

Other external factors also influence the uptake of electric vehicles in different regions. For instance, businesses that profit from the conventional private automobile market has a low interest in EV adoption and will work to delay it (Rietmann & Lieven, 2019). When the aforementioned factors are combined, they increase EV uptake, as Rietmann & Lieven reported (2019). Their model demonstrated that regulations, financial incentives, and the availability of charging infrastructure all contribute to the uptake of electric vehicles. They examined the interaction between these factors and concluded that the relationship between financial incentives and the maturity of the charging infrastructure has a very positive effect on EV adoption. This was also observed by Yao et al.(2020), who found that the US and Korea had comparable policy incentives to Norway in their model; however, Norway had a higher rate of EV adoption.

4. Needs for charging infrastructure

Access to home charging is critical for EV adoption, and recent research indicates that between 50% and 80% of charging occurs at home (Hardman et al., 2018). This section will discuss the charging requirements and how they vary by country. Numerous researchers examined the daily driving range in comparison to the BEV range. Pearre et al. (2011) investigated the case in which EVs are assumed to charge at home each night and start the next day with a full charge. They discovered that a large population of drivers can meet their driving needs with affordable BEVs after monitoring 470 vehicles for more than 50 days in Georgia. The study notes that more drivers can meet their needs on certain days by charging during the day; they refer to this as "day requiring adaptation." Jakobsson et al. (2016) expanded on the study's findings in Germany and Sweden by analyzing annual vehicle kilometers traveled (VKT) for single- and multi-car households to determine the days that require adaptation. According to them, drivers with an annual VKT of more than 40,000 must utilize public charging at least once a week.

Funke et al. (2019) conducted an international comparison to determine the extent to which charging infrastructure is required. These requirements vary according to a variety of factors. Most importantly, private home parking is available (Kutty et al., 2020). The Gini indices, car dependence, GDP per capita, the share of the urban population, population density, and average daily driving distances are also considered. For instance, in the Netherlands, where the number of detached houses is low, a large number of public slow charging stations have been constructed to serve as a substitute for home charging. On the other hand, countries with a high proportion of detached houses require less public slow charging. Additionally, fast-charging stations are required on highways for long-distance trips and in densely populated areas where a private parking is unavailable. Analyze data from real-world charging stations and the number of BEVs per million population. Nicholas and Hall (2018) report a different number of BEVs per charging station in different countries, because each country's regulatory framework is unique, as discussed previously. According to Chakraborty et al., (2019), the price of electricity in various locations (home, work, public) has a significant effect on the charging location selection. Finally, studies indicate that additional research is necessary to determine the appropriate level of charging.

5. Possible locations for EV charging stations

Identifying potential locations for EV charging stations is critical for the station's effective use. This can be accomplished by gaining a better understanding of EV users' preferences and selection criteria for potential locations. For instance, fast charging stations could be located at highway service stations, existing gas stations, or shopping centers (Philipsen et al., 2016). In Japan, fast charging stations could be located at parking service providers or gas stations. Similarly, Tesla superchargers are located throughout Norway in shopping malls, cafes, and roadside restaurants. In the United Kingdom, fast and slow charging stations are located in a variety of locations, including train stations, airports, shopping malls, and supermarkets (Deb et al., 2018). This demonstrates that charging stations are strategically located near points of interest (POI). In the Netherlands, two strategies for locating EV charging stations were used. The first strategy, dubbed "demand-driven," positioned charging stations near users' homes based on their requests. The second strategy was to locate stations near public amenities such as shopping malls and government buildings. When analyzing the "demand-driven" charging stations, it was discovered that they were not evenly distributed throughout the city and were concentrated in high-density areas, because EV drivers lack access to private home charging. As a result, strategically located charging stations were utilized by a greater number of unique users but at a lower rate. The study concluded that both strategies complement one another because they were successful at achieving distinct objectives (Helmus et al., 2018).

Several location models could be used to optimize the allocation of EV charging stations, depending on the model representing demand. The path-based traffic volume (flow) can be used to capture the majority of traffic in the flow-capturing location model (FCLM). Hodgson pioneered this model (1990). When considering demand as concentrated in a single location, multiple location models are available. Hakimi's (1965) P-median location model minimizes the sum of distances traveled from various demand points. Hakimi (1965) also introduced the p-center model, which aims to locate the facility as close to the demand point as possible. The set covering model seeks to locate the fewest possible facilities necessary to service all demand points within a specified radius. This model is frequently used to allocate emergency service stations. A disadvantage of set covering is that it ignores the quantity of demand and assigns equal weight to all demand points. Church and Velle's (1974) maximum coverage model addresses this issue by accounting for the size of demand at each point and aiming to capture the majority of demand within a specified budget within the critical coverage distance. These models were used in studies with a variety of different objective functions. The primary optimization objectives were to reduce the distance to a charging station, reduce the cost of infrastructure for a given demand, and to maximize the number of EVs charged.

6. Electric vehicle demand estimation

Effective EV charging station allocation is contingent upon the method used to estimate demand and an understanding of where actual charging demand exists. The node-based approach is predicated on the assumption that demand is concentrated at a single point. In some studies, the population distribution is used as a proxy for determining demand (Brown et al., 2021; Sun et al., 2020). S.Y. He et al. (2016) estimated a community's charging demand using a variety of demographic data, including family size, income, and age. Sadeghi-Barzani et al. (2014) estimated demand using vehicle ownership data from each region. These demand points may not be accurate, as the concentration of EVs does not always correspond to the location of charging stations. This is especially true for EV owners who have access to home charging. Frade et al. (2011) estimated demand in two ways: for nighttime demand, they used population data, assuming that EV users lack access to home charging; for daytime demand, they looked at the type of buildings and employment in a region. Liu (2012) estimated a region's charging demand using the distribution of gas stations as a proxy. Another approach is path-based demand estimation, which makes use of traffic volume data and thus requires more data than the static node-based approach. Jochem et al. (2019) used traffic volume data to estimate the demand for fast charging stations on highways. Other researchers employed a tour-based approach, which necessitates the collection of significantly more data. This approach makes use of travel data from individual users. Dong et al. (2014) used GPS tracking data from users to model the demand for EV charging in a study. Pan et al., (2020) analyzed the trip destinations of 5183 drivers who participated in a travel survey.

7. Conclusion

The development of "Smart, Green, and Integrated Transport" is a major challenge around the world and it requires comprehensive research, and cross-sectorial collaborations involving governments, the automotive industry, and society. Although EVs have a strong potential to reduce the environmental impacts associated with transportation, deciding whether electric vehicles are better than conventional gasoline engine vehicles or not is not a straightforward task (Alsarayreh et al., 2020; Kutty et al., 2020b; Kutty et al., 2022a). The performance of EVs significantly varies based on spatial and temporal variations (Elagouz et al., 2022). For instance, internal combustion engine vehicles perform better than full battery EVs in some of the states in the USA, mainly due to the high dependency on coal and petroleum in electricity generation (Onat et al., 2015). EVs perform much better environmental performance if they are charged using solar charging stations (Onat et al., 2014). Sustainability impacts (carbon emission reduction potential, energy saving potential, life cycle cost, etc.) associated with electric vehicles varies significantly depending on driving patterns (e.g. the distance in a single trip), type of electric vehicles (Plug-in hybrid with different ranges, hybrid compressed natural gas and electric engines, full battery electric vehicles), the source electricity generation (natural gas dominated electricity generation mix, or solar charging stations) (Onat, 2015a; Onat, 2015b; Samaras & Meisterling, 2008; Smith, 2010) and the location of charging infrastructures and source availability. Furthermore, usually, electric vehicles are smaller than their counterparts and therefore, require less land use in terms of the road. They indirectly can contribute to the capacity of roads. Widespread adoption of electric vehicles might change road expansion plans to some degree or might decrease congestion to some degree (Abdella and Shaaban, 2021; Abdella et al., 2019). All these impacts should be quantified in terms of their impact on energy use, cost, emissions, etc. which requires the introduction of several customized modeling and optimization suits. Furthermore, a significant drawback of the set covering model used to optimize the allocation of EV charging stations was the use of equal weights for all the demand points. Weighting has been a significant issue in many transportation and sustainability-related studies when planning demand and optimal allocation. For future research, the authors suggest using statistical based weighting techniques such as the penalized weights (see Kutty et al., 2020a; Abdella et al., 2020; Abdella et al. 2020a; Abdella et al., 2021), Data Envelopment Analysis (DEA)-based weights (Kutty et al., 2021; Kucukvar et al., 2022; Kutty et al., 2022) and, Principal Compound Analysis (PCA)-based weights (Elhmoud et al., 2021). Regulation, public sector incentives, and policy development play a significant role in either success or failure of intended outcomes (Kutty et al., 2020). To achieve widespread adoption of EVs, consumers need to have access to charging infrastructure, and thus, optimal allocation of charging stations and policies to reduce the life cycle cost of these vehicles are very important to enhance market penetration of eco-friendly, efficient vehicle technologies.

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