The Charging Behaviour of Private Electric Vehicles

Subjects: Transportation

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Electric mobility is one of the ways of containing greenhouse gas and local pollutants emissions in urban areas. Nevertheless, the massive introduction of battery-powered electric vehicles (EVs) is introducing some concerns related to their energy demand. Modelling vehicle usage and charging behavior is essential for charge demand forecasting and energy consumption estimation. Therefore, it is crucial to understand how the charging decisions of EV owners are influenced by different factors, ranging from the charging infrastructure characteristics to the users' profiles.

Keywords: electric vehicles ; charging behavior ; private electric mobility

1. Introduction

The switch to electric mobility is one of the ways of containing emissions of both greenhouse gas and local pollutants in urban areas. Electric vehicles (EVs) come in different types, such as pure or battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). BEVs are electric vehicles that rely solely on batteries to transmit energy. BEVs need an external source of energy to recharge the batteries. HEVs use both an internal combustion engine (ICE) and an electric powertrain, which can be combined in various ways. PHEVs also have both an ICE and an electric powertrain, but unlike HEVs, electric propulsion is the primary driving force. These vehicles require larger battery capacity than HEVs and can be recharged directly from the grid. FCEVs are powered by fuel cells that use chemical reactions to produce electricity. The electricity generated by the fuel cells drives the wheels through an electric motor, and any excess energy is stored in storage systems like batteries or supercapacitors [1]. The focus of the present study is on the charging behaviors of BEVs and, partially, PHEVs. The widespread adoption of electric vehicles hinges on two key factors: technological advancements and market acceptance. In order to optimize vehicle costs, electric vehicle manufacturers strive to select the best battery technology that ensures both safety and performance, including long-range autonomy and high power [2]. To facilitate the adoption of EVs and make their widespread use feasible, it is necessary to develop an adequate charging network [3][4]; this, in turn, involves the correct planning that satisfies real demand. Elements such as power request, charge duration, and the spatial and temporal distribution of demand influence the planning and subsequent utilization rate of charging infrastructure, the emissions associated with the generation of electricity for charging, and the impact of charging on grid electricity [5][6]. For these reasons, understanding and predicting charging behaviors with sufficient accuracy are essential. It is thus important to elucidate how the charging decisions of EV owners are influenced by external variables related to charging infrastructure and mobility needs, by intrinsic socioeconomic and psychological factors, and by charging network design, which could also maximize utilization rates and user satisfaction.

Electric vehicles can be charged at various locations and speeds, and the costs may differ. EV supply equipment (EVSE) can be composed of one or more charging points (CP), which connect the power grid to the electric vehicles, drawing AC power to charge the EV battery in DC form. The converters can be either onboard or offboard, depending on the type of charging. The chargers can be classified into two categories: 'level' and 'mode'. Charging levels have been defined by the Society of Automotive Engineers (SAE), while the four charging modes are defined by the International Electrotechnical Commission (IEC). 'Level' refers to the power and voltage of the charging system, while 'mode' refers to the electronic communication between the vehicle and the power supply. This communication is critical for ensuring safety and proper charge control. The International Electrotechnical Commission (IEC) has defined four charging modes [7].

Mode 1 refers to home charging directly from a standard power outlet with a simple extension cord. However, this charging method does not provide shock protection against DC current. Moreover, mode 1 is prohibited in many countries. Mode 2 charging involves the use of a special cable, provided with the EV, with integrated shock protection. Mode 3 charging involves a dedicated charging station or a home-mounted wall box for EV charging. Both provide shock protection against AC or DC currents. In Mode 3, the connecting cable is provided with the wall box or charging station. Mode 4 is mainly used for DC fast-charging applications. In this mode, AC is converted to DC in an external charger, which is then used to charge the EV battery. In the first three modes, the EV is directly connected to the AC distribution network, and the conversion to DC takes place in the vehicle. In mode 4, the conversion takes place in the charger.

Level 1 charging corresponds to 120 AC voltage with a power of 2 kW; it is typically used in residential settings and does not require special equipment. It is not allowed in the EU. Level 2 corresponds to the standard European 230/240 V AC plug. It can be used for domestic charge or in public charging poles. The delivered power usually ranges from 3 kW to 20 kW. Level 3 indicates quick-charging stations using high-voltage direct current (DC), typically 400 V DC. The charging power of these stations ranges from 50 kW up to 130 kW. Level 4 chargers use 400–800 V DC voltage, with a power level up to 500 kW, and are mainly intended for long-distance driving and heavy vehicles [8][9].

The need for an in-depth analysis of the real and potential charging demand has led to a significant number of studies on EV energy demand modeling, conducted at different levels of aggregation depending on the purpose of the study. Disaggregated approaches directly consider individual patterns of mobility and EV recharge, whilst aggregated ones often start from the energy demand of the EV supply equipment (EVSE). These approaches are not mutually exclusive, and the data from different sources are often combined to model EV loading.

The characterization of charging behavior is inextricably linked to the diffusion of EVs. Indeed, the individual characteristics of EV users also influence charging behaviors. EV users are often male and middle-aged and typically have higher levels of education, an above-average income, and multiple cars per household [10][11][12], corresponding to the profile of early EV adopters [13]. With the spread of electric mobility, this audience tends to widen and include different user groups with presumably diverse needs and behaviors.

In fact, the propensity to adopt EVs depends on many factors, both economic and psychological, investigated in the literature. Economic studies usually compare the alternatives between different types of vehicles described by their characteristics, based on which consumers make decisions by making trade-offs between attributes. Psychological studies focus on motivations by examining the influence of a broad range of individual-specific psychological or social constructs [14]. Financial, technical, and infrastructural factors have a significant impact on the choice of switching to EVs, while psychological variables have a stable effect demonstrated by several studies. The influence of socioeconomic and demographic variables is still unclear and sensitive to small changes [14]. However, early EV users show some prevalent characteristics, such as a high level of education and a high income, being predominantly young or middle-aged males, living in large families that own more than one car, and living in small to medium-sized cities [10]. Having experienced EV driving and one's awareness of environmental values are factors that dispose one to the purchase of an electric car [15], as well as satisfaction with use, which appears to be high among both experienced and novice EV users [16]. Adding vehicle-to-grid functionality seems to be an option that tends to favor EV adoption, probably because it can represent a possible economic income for owners [15]. The self-perception of belonging to a specific category of people and the perception of the electric car as a status symbol seem to positively influence the decision to purchase [17][18].

Increasing experience with EVs raises awareness of many aspects of electric mobility. For example, battery range was rated less critical for people who have owned EVs longer than neophytes or conventional car owners. On the other hand, charging anxiety seems less present among early adopters, while potential users appear more concerned of not having enough autonomy or sufficient charging infrastructure [19]. Battery life is considered a more critical factor for internal combustion engine vehicle (ICEV) owners than EV owners [15], although it has emerged that range and battery charging are the two main reasons for dissatisfaction among EV users [16].

2. The Charging Behaviour of Private Electric Vehicles

2.1. Influence of Mobility Choices

Commuting routines and planned trips have a significant impact on EV-charging choices. According to some studies, charging habits tend to follow traffic patterns, indicating a lack of a well-defined charging strategy. As a result, EVs are often charged immediately upon arrival, leading to spikes in demand [20][21]. A distinction concerns the decision of whether to charge during the journey or at the destination. Charging on the go can influence route choice, as it can involve detours taken to reach a CP, and mainly concerns occasions when EVs cannot complete a journey with their available battery energy. The increase in battery autonomy has made this occurrence uncommon in urban areas [22].

The charging decisions of electric vehicle (EV) owners are influenced by their travel choices, which, in turn, are affected by various factors, such as personal preferences, income, age, gender, and education level [23][24]. The duration of scheduled stops is a significant factor that impacts charging decisions. Longer stops increase the likelihood of EV drivers charging their vehicles [25]. Parking time also impacts charging choices: private chargers are usually used at night, and public charging is generally carried out during the day. Additionally, the selection of a charging station depends on various factors, such as charging duration, proximity to the origin, and consistency with the direction of travel [26].

Regarding driving habits and distances traveled, EVs are often used for urban journeys with limited mileage [27][28][29]. A European study found that 75% of observed cars travelled less than 47 km daily, while rental EVs travelled a daily average of 66.5 km [30]. In urban settings, the authors of [31] found that over 71% of distances traveled were less than 15 km, and about 76% of parking events lasted less than 1 h. An early English trial [32] revealed that the length and average duration of the journey are 9 km and 15 min, respectively. A UK survey showed that only 10% of the respondents drove more than 40 miles a day, and around 30% used EVs for their daily commutes, while around the same percentage used them between 4 and 6 days a week [27].

Studies also show a difference between the charging habits of owners of PHEVs and BEVs [33][34][35][36]. Both types of EVs rely on home charging as the main source of energy [35][37][38]. The analysis reported in [39] on the recharging behavior of PHEVs in North America highlights the habit of night recharging and the non-intensive use of additional recharging. Hardman et al. [40] reported that PHEVs are recharged less often than BEVs at public stations or along long-distance corridors. Overall, long-range BEVs are connected more frequently than short-range ones, while the opposite is true for PHEVs [34]. PHEVs are generally recharged at lower SOCs than those for BEVs [38].

2.2. Use of Infrastructure

Analyses of charging behaviors cannot ignore the availability and composition of charging infrastructures and the context of the areas analyzed. This means that the results obtained for specific geographical areas in the literature have limited applicability to other countries. Nonetheless, there are some charging behaviors that are common among most EV users, such as the predominance of home charging, where it is available [40], and the important role of workplace-charging infrastructure for EV commuters [35][41]. Concerning the choice of where to charge, generally, public charging infrastructures are used differently depending on their location in a city [42]. According to a Dutch study on public CPs [43], roadside charging accounted for 62.86% of all sessions, while charging near one’s home accounted for 27.84%, and charging sessions near one’s workplace amounted to 9.3%.

A general preference for home charging was identified in many studies [40][44], followed by workplace and public charging [40][45][46]. According to the IEA, approximately 89% of charging stations are private, located in places of convenient access, such as at home or in offices [1]. According to a survey conducted by the European Alternative Fuel Observatory (EAFO), 76% of EV users in the EU charge their EVs at home, while around 20% do so regularly at work [44]. These results are in line with those obtained in the UK [27][47] and Germany [13], although there are some variations in the distribution of percentages. In the USA, about 80% of recharging takes place at home [48][49], and about 50% drivers use this mode exclusively [34]. In addition, in British Columbia, most users have access to home charging [50]. The availability of CPs at work represents an important opportunity [51], especially for users without access to home charging [44]. Users who charge exclusively at work usually have unlimited free or paid access to work CPs [34]. However, free or over-subsidized charging can lead to the inefficient use of CPs if there is no incentive to move a vehicle after the charge is over [52], and this type of charging can encourage plugging in even if the remaining range is enough for subsequent trips, creating congestion for chargers [36]. Furthermore, free charges are not financially viable and could discourage future charge investments by employers. Therefore, suitable pricing policies can significantly influence the use of charging in the workplace [52][53].

Public charging infrastructure can be a valuable alternative for areas with limited home-charging options, particularly densely populated urban areas [54]. Personal safety and proximity to one’s home are the most crucial factors in the replacement of private charging with public charging, particularly during nighttime usage [55]. Additionally, public charging infrastructures are used differently depending on their location [42]. In [43], the authors state that public charging along the streets accounts for 62.86% of all sessions, while charging near work amounts to 27.84% of the total, and charging sessions near home make up 9.3%. Public and corridor charging stations are the least-used types of infrastructure [40][56]. An overall analysis of charging demand revealed that the likelihood of using public charging in a given area is proportional to the average number of cars per family and inversely proportional to the percentage of private homes in an area [57]. Fast charging is a promising technological solution that can positively impact the spread of electric vehicles. By reducing charging times, it can potentially increase user acceptance of electric mobility. A questionnaire distributed in Germany revealed that motorway service stations, shops, and traditional refueling stations are ideal locations for fast-charging stations. EV users are willing to take a detour to find fast charging stations, but they reject waiting times [13]. Users are also willing to pay more for fast charging compared to slow charging [25][58].

The connection profiles differ between weekdays and weekends, with about 25% of the total energy supplied during the weekend [56]. Another characteristic that emerges is that the dwell times at the CP are generally much longer than the actual recharge times, with inactivity percentages ranging from about 40 to 75% [21][30][56]. The idle time, i.e., the period in which an EV is parked without charging, lasts on average 4 h, although it depends on the CP's position and its charging power [59]. Slow charging points typically have much longer dwell times than fast ones [42][45], leading to high operational inefficiency [42][59][60][61]. In general, the shortest stays are recorded at road CPs, and the longest are recorded in office and public access car parks [30] and at residential CPs [62]. As a result, the average charging power rates are often significantly lower than the nominal power [42][63].

The temporal distribution of recharges depends on various factors, including geographical and social variables (work start and end times, commuting rates, etc.). However, a peak can usually be observed in the morning when leaving for work and later when arriving at work, as well as in the evening when returning home, especially for slow charging [64][65] and domestic charging [66]. On weekends, domestic charging is more evenly distributed throughout the day [67]. Fast charging is used more during the day [64], with very short idle times of 48 min on average [43][60].

Fast DC stations show a utilization rate nearly three times higher than AC CPs [62][63]. Indeed, European EV owners consider charging speed one of the most important characteristics of a public CP. However, the frequency of use of fast chargers is 10% in the EU, which can be compared to 21% for public slow chargers [44]. This result may be attributed to a minor diffusion of fast chargers compared to slow ones. An adequate public charging network seems to favor the adoption of electric mobility [1][58][68][69][70], but there is no unanimity regarding which alternative, slow or fast, is more important for the diffusion of electric mobility [54][58][68].

The usage patterns of electric vehicle charging stations differ depending on whether they are residential or public. Residential charging occurs mainly at night and is spread out evenly across the week. Public charging, on the other hand, happens mostly during the day and is concentrated on weekdays [62]. Public charging usage is also affected by seasonal changes, with holidays having a particularly significant impact. AC charging stations are more frequently used for weekday and daytime charging, while DC fast charging stations are more popular on the weekends [29][43][62]. The temporal distribution of public station usage also depends on where these stations are located [71].

2.3. Sensitivity to Costs

When and where to charge depend on the service cost. The charge price negatively affects the infrastructure choice, while parking opportunity has a positive effect [22][72]. However, some users are more time-sensitive and do not wish to deviate to save money [27]. The possibility to pay via credit card at public charging stations also appears to be an important factor for EU BEV drivers [44]. Drivers often prefer to charge electric vehicles at home or work rather than at a public charging station, as the price is lower [40][73][74][75]. Offering reduced charging prices during certain time slots can have a positive impact on the choices made by infrastructure users, even if the savings are marginal [76]. However, free charging at work can lead to unintended consequences, as it can encourage people to connect even if the residual autonomy is sufficient. This can result in congestion at charging stations, which can inconvenience those who need to charge at work to complete their daily commute [75]. Moreover, providing free charging is not financially sustainable and may discourage employers from investing in charging infrastructure in the future.

2.4. Classification of Charging Behaviors

The identification of groups of users with similar charging behaviors can be helpful in determining charging demand in different scenarios.

Applying clustering techniques to a set of charging sessions revealed four prevalent charging behaviors. The first is the morning behavior, with an average connection duration of 8.5 h, which is primarily associated with charging at work. The second is the daytime behavior, with an average duration of 1.5 h. The third and fourth behaviors are afternoon and evening charging, with average durations of 4.5 and 15 h, respectively. These charging behaviors are mainly associated with home charging [77]. An analysis of approximately 5 million charging transactions at public charging points identified 13 main behaviors. The most prevalent of these are night-time charging at home and charging at work. For quick charges, there are a variety of behaviors linked to different types of users and purposes [78]. According to a survey of electric vehicle (EV) owners in the United States, there are three main types of charging behavior. The first type is charging an EV based on price and need, while the second type is recharging a vehicle whenever there is an opportunity. The third type concerns a wider range of factors, such as charging power, dwell time, and the cost of home charging [25].

2.5. Autonomy and Charging Anxiety

The perception of SOC is closely linked to the evaluation of EV residual autonomy and varies from person to person based on their choice of charging. Accurate assessment of residual autonomy is associated with the concept of recharging anxiety [79] and risk attitude [11].

Overall, the studies place emphasis on battery SOC, charging time, and prices. Battery SOC is considered to be among the most influential factors when modeling charging choices [20][80][81][82][83][84][85], although its distribution at the beginning of the charging period seems to depend on the type of charging infrastructure used: the higher the power, the lower the initial SOC [85]. From the data collected in pilot studies, surveys, or recharging data, it can see a tendency to recharge when the SOC is quite high, around 50%, even if the range is sufficient to complete subsequent trips [27][30][86], which means that users tend not to use the full capacity of a battery but connect their vehicle as soon as they have the opportunity. This tendency is particularly true for home or private charging, especially regarding overnight charging [31]. Morning charging near multi-family homes occurs with a lower initial SOC than charging near single-family homes [38], and public charging, especially fast forms, has the lowest initial SOC values [29][38][65]. Users tend to overestimate the importance of battery SOC in the charging decision, particularly for short trips [87], and tend to charge their batteries at a high SOC [31][38][42][64][88][89]. These findings may suggest that people tend to charge based on the availability of charging opportunities rather than necessity. Additionally, one may overestimate the need for charging by focusing on the state of charge (SOC) instead of the available range, especially for shorter trips and larger batteries.

Risk attitude is another important element in charging behavior characterization: risk aversion leads to focusing mainly on the remaining range, while risk-tolerant users tend to balance the cost of recharging with the remaining battery autonomy [72]. The degree of recharging anxiety depends on many factors, such as infrastructure availability, travel plans, and understanding of a battery [27]. Technological knowledge, driving experience, and risk aversion play positive roles in alleviating this stress [22][90][91]. However, range stress also depends on other factors, such as the driver’s gender and age. Two studies have produced conflicting results on the relationship between gender and risk perception.
Distances between consecutive recharges tend to be shorter than the average daily distances, which suggests that EV drivers prefer to recharge whenever they have the opportunity, irrespective of the remaining range [48][88]. Most private EV users charge their batteries almost completely, indicating a preference for maximizing the amount of electricity obtained from each charging event [31][42].

2.6. Socioeconomic, Cultural, Environmental, and Experiential Factors

Conducting questionnaire surveys with users is a useful tool for analyzing the various factors that affect their private charging behaviors. However, due to the complexity of the topic and the challenges involved in isolating the influence of different variables on behavior, it can be challenging to provide conclusive results.

A study conducted by Xu et al. [92] explored the factors influencing the choice of charging mode and location among around 500 BEV users in Japan. This study found that a battery’s capacity and state of charge, the possibility of overnight charging, and the number of previous fast charging events were the key factors influencing the users’ choice of charging mode and location. Additionally, the interval between the current charge and the next trip positively impacts the choice of slow charging at home or work. Another survey conducted by Anderson et al. [93] involving approximately 4000 EV users identified the price, occupancy rate, waiting time, and distance of the charging infrastructure from the point of interest as key determining factors in the choice of charging. In another study [94], a random utility model was proposed based on stated choices for home charging preferences. The results of this study indicated that the amount of energy to be recharged had a positive marginal utility in most cases, while the actual charging time had a more complex influence. Most users preferred to keep their vehicles charged as long as they were home and avoided ending charging if it caused delays in their departure. The charging cost, on the other hand, always had a negative marginal utility.

According to the concept of User–Battery Interaction (UBIS) analyzed by Franke and Krems [95], the psychological approaches adopted by charging users are different for those with low and high UBIS. Users with low UBIS have lower awareness of the battery levels of their devices. Thus, they tend to recharge based on contextual triggers rather than the battery charge level, with the latter being the case for users with high UBIS. Moreover, the survey revealed that personality traits such as self-control, low impulsivity, and greater competence with respect to the system were positively correlated with reduced autonomy anxiety.

Recently, the service experience at charging stations has been recognized as being influential in the charging decision process [22][82][96]. Analyzing the impact of the service level of charging stations on user choice, it has emerged that high satisfaction scores of previous users and short queuing times attract more EV drivers [22]. The cited study identified two types of decision-making models among the participants: (1) those who prioritize service quality, which represents the majority of the interviewees and includes younger drivers with more driving experience and higher incomes, and (2) those who consider multiple factors, such as range, parking time, and charging fees, known as pragmatic drivers. A recent study [97] revealed that individuals with higher income levels who travel longer distances tend to opt for public charging infrastructure. On the other hand, those who prefer charging their electric vehicles at night and are more sensitive to charging prices are likely to be more satisfied with private charging infrastructure.

3. Summary

Transport contributes largely to noxious emissions, both greenhouse gases and local pollutants. The electrification of vehicles is leading to a significant reduction in these impacts. A reliable and available charging infrastructure is essential to facilitate the diffusion of electric vehicles. Consumers are becoming more environmentally conscious and are seeking sustainable transportation options. To ensure a smooth transition, it is important to understand the commuting and travel needs of users and how well these needs can be met by electric vehicles. To this end, many studies have been dedicated to analyzing the recharging of EVs, for public, commercial, or private vehicles. Examining what influences private charging behavior is possible through user surveys and the analysis of mobility and charge data. Due to the vastness of this topic and the difficulty of isolating the impacts of various variables on behavior, it is challenging to provide definitive results. Several factors influence charging decisions, including gender, risk aversion, type of travel, availability of charging stations, travel distance, and SOC perception. Destination, parking duration, charging time, price, subsequent travel distance, and travel chain type all impact EV charging [11][40][75][98].

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