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Adoption barriers for electric vehicles: Experiences from early adopters in Sweden

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ABSTRACT

Electric vehicles are considered as one of the most effective technologies for reducing current greenhouse gas emissions from the transport sector. Although in many countries, local and national governments have introduced incentives and subsidies to facilitate the electric vehicle market penetration, in Sweden, such benefits have been limited. Results from a survey carried out among private owners of electric vehicles are presented in this paper, including the analysis of the respondents socio-demographic characteristics, reasons for choosing an electric vehicle, charging locations and driving preferences, among others. The main results characterize current electric vehicle drivers as male, well-educated, with medium-high income; electric vehicles are used mainly for private purposes and charged at home during night time. Furthermore, the paper presents an analysis of the impact of large-scale penetration of electric vehicles on existing power distribution systems. The findings presented in this paper provide important insights for assuring a sustainable large-scale penetration of electric vehicles by learning from the experiences of early adopters of the technology and by analyzing the impact of different EV penetration scenarios on the power distribution grid.

1. Introduction

In 2009, the transportation sector was responsible for 25% of the worldwide carbon dioxide (CO_2) emissions, out of which 75% was produced by cars and trucks [1]. In the European Union (EU), road transportation contributes to one-fifth of the total CO_2 emissions which has led the European Commission to set targets such as 10% renewable transport fuels by 2020 [2]; or adjusting the CO_2 emission limits for all new cars from 130 g of CO_2/km to 95 g of CO_2 by 2020 [3]. Not surprisingly, with the increasing concerns regarding rising GHG emissions and secure oil supply, the development of low-carbon and carbon-free technologies for transportation has been given a high priority for policy makers and different authorities worldwide [4]. Alternative fuel vehicles have increasingly gained attention due to their potential for reducing greenhouse gases (GHG) emissions and their ability to increase the penetration of renewable sources into the transportation sector. Development of cost-competitive second and third generation biofuels as well as large-scale market penetration of Electric Drive Vehicles (EV) for commercial and private use, have become the main focus of investments in Research, Development and Demonstration programs [5].

Although electric vehicles have been around since the 1800s [6], it was not until 2011 when commercial EVs gained high interest, mainly due to environmental concerns, as well as advances in batteries and electric drive-train technologies (e.g. regenerative breaking) [4].

Typically, the term *EVs* refers to different types of vehicles, for instance plug-in hybrid electric vehicles (PHEVs), extended-range battery electric vehicles (E-REVs), battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). This paper will focus on the owners of BEV, thus excluding all the hybrid models.

Regarding the EV market uptake, their penetration levels are strongly dependent on the consumers acceptance. On one hand, potential changes in travel behavior, governmental support and the environmental and economic concerns are some of the additional key factors that have acted as barriers to rapid and successful EV market uptake. On the other hand, higher price than conventional vehicles, is one of the main reasons for the weak demand in many countries. Additional concerns, such as the so called range anxiety,

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referring to the anxiety caused by the limited driving range of the batteries versus the range offered by their internal combustion engines (ICEs) counterparts, batteries charging time and lack of charging infrastructure versus the use of fossil fuel stations [7] also limit mass adoption of EVs. However, a study carried out in UK, evaluated the charging behavior of EV drivers, and found that the initial range anxiety would fade overtime since knowledge and confidence developed through driving for an extensive period of time [7], [8].

Zubaryeva et al., summarized different criteria affecting the success of EVs market penetration: demographic criteria (e.g. early adopters usually have high income; wealthier countries will adopt earlier); environmental criteria (e.g. temperature variations); energy criteria (e.g. including electricity mix; energy security); and transport criteria (e.g. market penetrations might be facilitated if it targets consumers interested in purchasing a second car) [9]. To identify and understand the main driving forces that explain the variables and the thought process of early EV adopters, could help develop better strategies and incentives to help increase its market penetration.

The aim of this paper is to identify the main factors responsible for motivating the use of EVs and to understand the thought process of early EV adopters, in order to shape the strategies and define better incentives that could help increase the market penetration of electric vehicles in Sweden. This country has been ranked several times as one of the most innovative countries in the world as well as environmental front-runner and pioneer [10], moreover, it has several characteristics that make the country very suitable for large-scale electric vehicle adoption, for instance, stable production and high capacity transmission of electricity, large share of renewable energy sources, with 44.1% generated by hydro [11], possibility for easy access to charging, etc. [12].

When it comes to the current levels of EV penetration in Sweden, the total amount of electric vehicles, including plug-in hybrid vehicles was of 8668 in February 2014, out of which 39% were fully electric and 61% plug-in hybrid vehicles [13]. Although there was a 142% increase between 2014 and 2015, Sweden still lags behind in comparison to other European countries, as for instance Norway, France or Germany.

The main gaps identified in research literature (and not based on hypothetical data) from EV drivers are the lack of studies using representative samples that include the experiences from EV early adopters as identified by Refs. [14,15]. A better understanding of EV drivers behavior is essential to determine the impact of EVs and to promote a successful and sustainable integration of EVs into current societies and infrastructures and to facilitate future EV market development and growth.

Moreover, filling these gaps would help determine changes in electricity demand necessary to estimate future infrastructure requirements and maximize existing resources, specially non-dispatchable renewable electricity. Integrating electric vehicles with existing power systems poses several challenges besides the economic and regulatory challenges, such as the technical limitations of the existing networks and the increase in distribution losses due to EV charging peaks.

In order to cover some of the research gaps and help eliminate some of the market barriers that explain the slow EV penetration in Sweden, this paper focuses on identifying and evaluating EV early adopters characteristics and experiences. The results are expected to provide important insights for policy development, marketing strategies and infrastructure requirements for a successful large-scale EV adoption. Additionally, other countries with similar characteristics can improve their initial EV implementation stages from the learned experiences in Sweden. To achieve this, a detailed survey was sent out to all the private electric vehicle owners in Sweden, gathering insightful information regarding their characteristics, driving experiences and suggestions for future improvements.

Additionally, in order to estimate the possible impacts on the existing electricity infrastructure, the information from the survey, regarding charging habits and average daily driving patterns, together with EV adoption forecasts [5], were used to analyze the impact of EVs on the existing power infrastructure. Moreover, studies and simulations from several researchers on this particular issue [16,17] were also presented and discussed. Finally, a simple simulation model was built to determine the technical implications on the local electric distribution infrastructure of the expected EV growth in Sweden.

1.1. Relevance of EVs

Electric vehicles have been proposed as one of the most effective alternatives to internal combustion engines (ICEs) to reduce CO_2 emissions and allow countries to increase their sustainability [18]. From an efficiency point of view, ICEs reach 28–30% conversion efficiency while electric motors can achieve up to 95% [19]. From an environmental point of view, when comparing the operation phase of ICEs and EVs, LCA analysis shows that gasoline vehicles cause a higher environmental impact. However, battery production is considered as the most critical component, depending on the type of materials needed for the manufacturing. As an example, when manufacturing Lithium-Ion batteries, CO_2 levels of 2.7 MT per battery have been estimated by Ref. [20]. In addition to the previously mentioned impact, Faria et al. have identified that the elevation profile, user driving style and the auxiliary equipment affect heavily the overall energy consumption of the electric vehicles [21]. Moreover, the electricity generation mix is also one of the decisive factors affecting the EV impacts on GHG emissions. With the current share of renewable sources in the electricity mix of many European countries, led by Norway with close to 100%, followed by Austria and Sweden with approximately 60% in 2012 [22], EVs would contribute to a substantial reduction of GHG emissions in these countries, with emissions expected to continue decreasing due to the continuous integration of renewable sources.

Another important aspect to consider is the impact that different penetration levels of EVs will have on the power system. Large penetration of EVs would not affect the power transmission and distribution systems, for as long as they are managed as active components of the whole power grid. With highly increasing use of renewable energy sources, Finn et al. demonstrated that, by combining renewable production with demand response management of EVs, grid operators and consumers would maximize renewable self-consumption, reduce the peak demand and minimize demand on conventional generation [23]. To minimize the impacts on the power system and avoid investments on new generation and transmission capacity, Madzharov et al. analyzed several scenarios of EV penetration, with controlled and optimized charging in different power systems, demonstrating the potential benefits with using controlled charging [24]. The idea behind *Smart Charging*, is that the EV or the charging station it is connected to, would communicate with the network operator and then it would send back information about how much power it could draw at any given time. This approach has been reported to help improve the integration of intermittent sources of energy into the electric grid [25]. An additional approach is to provide with *vehicle-to-grid* (V2G) functionalities, where EVs are allowed no only to recharge from the electric grid, but also to supply power from their batteries when required. V2G would allow EVs to play an important role in increasing the flexibility of the distribution power system and to facilitate the integration of fluctuating distributed energy sources by providing with a large storage capacity. At national level, large scale V2G was simulated by Lund and Kempton, for the case of Denmark with high use of wind power [26]. Two types of energy systems were included in the model, one with a large share of combined heat and power (CHP), as it has been predicted for Denmark for 2020, and another without CHP; results showed that a combination of buildings and electric transportation, could facilitate the integration of very high levels of wind power capacity, without needing centralized storage and without compromising the power systems reliability [26].

Summarizing, electric vehicles constitute a promising solution for reducing CO_2 emissions, and when actively integrated with the existing power distribution grid, they can even facilitate larger penetration of renewable energy sources.

1.2. The role of incentives in the consumers acceptance

As described in the previous section, from a technical and environmental point of view, electric vehicles are considered a promising solution to mitigate GHG and other emissions as well as to boost energy security and facilitate the integration of renewable energy [27]. However, the levels of EV market penetration have been rather low in many countries, typically due to the low levels of acceptance of the drivers. High prices of EVs when compared with conventional vehicles, constitutes one of the first barriers preventing drivers from purchasing an EV. Larson et al. [27] found that the consumers included in their study were unwilling to pay a substantial premium for an electric vehicle; additionally, most of the consumers claimed that sources of information regarding EVs should be easily accessible, objective and trustworthy in order to help them increase their knowledge and thus allow the consumers make a more informed decision when purchasing a vehicle. Additionally, different research results show that the intention to purchase an EV is affected by the consumers demographic characteristics, their perceived lifestyle, and expectations regarding price development [28].

In order to overcome the market uptake barriers and encourage more consumers to buy electric vehicles, state and local governments in many countries have initiated incentives and subsidy programs as well as proposed new policies. Incentives for purchasing and using EVs have been divided by Proff and Kilian into monetary and non-monetary parameters. Monetary parameters include: financial incentives, tax relief, toll-fee exemption, free parking, and free recharging stations [29]. Non-monetary parameters comprise the increasing the driving range, allowing the use of bus lanes, charging times and options, entry to the city center and zero emission zones, modern/new vehicle architecture; social and ecological benefits; and additional functionalities of the EVs (e.g. self-driving).

The incentives and subsidies are usually based on national adoption level goals and EV market uptake. In countries throughout Europe, EV adoption targets have been set by the governments, in relation to the European goals (to reach 8–9 million EVs by 2020). The French government set the National targets to 2 million vehicles; while Germany, Spain and The Netherlands are each targeting to reach 1 million EVs. One of the most outstanding cases in Europe is Norway: in September, October and November of 2013, EVs were the most sold type of vehicle in the country. In 2009, the country installed an extensive charging infrastructure which combined with high financial incentives, allowed the country to become one of the top users of EVs [30]. To promote the use electric vehicles, the Norwegian government offers approximately 17.000 EUR for the purchase of a new electric vehicle [31]. Additionally, EV drivers have access to bus lanes; pay only 50 EUR annually for the motor vehicle tax; and can park and charge for free at publicly funded charging stations. Exemptions on purchasing tax, toll roads charges, taxes related to registration and the yearly circulation tax, have also helped drivers in Norway to choose to buy an electric car when purchasing a new vehicle.

On the negative side of such incentives and subsidies, some authors argue that EV owners mainly use these types of vehicles for acquiring a second car, suggesting that EVs are used to replace short trips that otherwise would have been done by other means of transportation, such as public transportation, cycling or walking [32]. Moreover, by providing free parking and access to bus lanes, they also argue that EVs were used by drivers from two of the towns with the highest ownership of electric vehicles in the country, as a motivation for driving to the Norwegian capital, Oslo, rather than using other forms of transportation.

In Sweden, the situation with governmental provision of subsidies and incentives for electric vehicles has not been as favorable as in the neighboring Norway. Since the 1970s, Sweden has been at the forefront of developing alternative fuel technology for personal vehicles. Due to the implementation of a strong policy framework requiring fuel providers to make renewable alternatives available at gas stations, the adoption of biogas and ethanol, flexi-fuel vehicles experienced a major expansion [33]. However, in early 2010, the negative environmental and social impacts of the first-generation biofuels negatively impacted the political support for alternative fuels. In consequence, politicians and government parties are now more cautious and conservative when it comes to adopting a strong policy framework in favour of EVs. Nykvist and Nilsson concluded in their analysis of the EV acceptance in Sweden, that there is a very limited awareness, experience of and knowledge of EVs [33]. This has resulted in misconceptions of the progress of the technology among planners, policy makers and consumers and thus, has led local governments to lean more towards increasing the incentives for public transportation instead of private. The existing direct subsidies have been that since 2012 and until 2014, cars in Sweden with CO_2 emissions of 50 g/km and less were entitled to receive a one time super green car premium of 40000 SEK (approx. 4290 EUR), although this was limited to a maximum of 5000 cars. Additionally, EVs in Sweden have been exempt from annual road tax. Overall, the incentives are not considered high enough to compensate the higher base price of EVs [34].

Despite the lack of large support from the government, the use of EVs has sustained a steady growth. In fact, March 2015 was the month with the highest number of EV registrations, with a total of 699 cars (including vehicles purchased by companies as corporate vehicles and as part of employee compensation packages), surpassing the previous record number reached in June 2014, when the number of registered EVs was 597 [13].

It is therefore, important to understand and detect the driving forces that have led early-adopters to choose EVs as well as to analyze their experiences and preferences that can help policy makers and governments to better prepare for a smooth and sustainable transition to mass-utilization of EVs (e.g. location of charging stations; new business models for charging consumers for the charging of their vehicles; etc.).

Research on evaluating the characteristics of EVs early adopters has been carried out in some countries. For example, when analyzing the main characteristics of electric vehicle owners in Norway, studies showed that EV drivers usually have a high income, higher education and their decision to purchase an EV was highly motivated by economic savings and/or environmental issues. In fact, 41% of consumer that bought an electric vehicle in Norway stated that saving money was the main reason for them to choose this type of vehicle [31]. In Germany, where a goal of reaching one million EVs by 2020 has been set by the Government [35], Plotz et al. analyzed early adopters of EVs from a demographic and attitudinal standpoint [36]. The study included individuals who were interested in buying an EV or already owned one. Middle-aged males living in multi-person households, with an interest in driving an environmentally friendly car, interested in new technologies and living in small cities were the main characteristics identified by the authors. Since the early adopters are full-time employed, they usually commute daily to work, thus drive a significant number of kilometers as they live in areas outside the cities. The large amount of kilometers driven with the EVs makes them attractive and more profitable from an economical and environmental point of view. Based on the findings of these and other studies on current EV drivers a survey was carried out to analyze the situation in Sweden.

The structure of the paper is as follows: a detailed description of the survey used and main questions used is presented in the Methods section; an in-depth analysis and discussion of the responses obtained are presented in the Results and Discussion section; and finally, the concluding remarks are presented in the final section of the paper.

1.3. EV integration in existing electric networks

Large penetration of EVs can affect existing electricity consumption profiles by increasing the peak consumption during the hours when the more amount of EVs are being charged. According to Masum et al. [37] who investigated this consumption peak increase on a 1200 node test system topology, found out that voltage violations would occur during the night peak with EV penetrations as low as 17%. Furthermore, a simulated EV penetration of 62% (the maximum penetration simulated) would increase total distribution losses by 500%.

Similarly, Petit and Perez [38], suggested that with uncontrolled charging, even though the peak energy demand could be covered in most distribution networks, operators might have to limit the peak consumption in order to prevent voltage violations. Additionally, controlled charging and Vehicle-to-Grid (V2G) strategies have been proposed by several authors [39–42] as a suitable option for integrating EVs on existing distribution networks. Furthermore, large penetration of EVs can help support renewable energy integration [25,26,38,43].

However, in order for these strategies to be effectively adopted, consumer perception and driving habits must be analyzed in order to determine the real potential and optimize the implementation of any of these schemes [7,14,28,44].

2. Methods

The following section presents the methods used to investigate EV user acceptance and use, together with the modelling approach used for testing the impact of EV penetration on distribution networks.

2.1. Survey

The main aim of this study is to gain knowledge about the demographic characteristics of current electric vehicle owners in Sweden as well as to gather information related to their car preferences, main use of the electric car, etc. A paper survey (in Swedish) was developed and sent out to the majority of electric vehicle owners registered as private users (e.g not registered as company vehicles). A list with all EV owners in Sweden was gathered with the help of the Swedish Transport Agency, from where private EV owners were filtered and included in the survey.

A total of 402 surveys were sent out in March 2015, out of which 3 were withdrawn due to wrong addresses, incomplete data, and two EVs registered to the same household. The total number of surveys sent was 399, and after a period of 3 weeks, 247 responses were received, reaching a response rate of 62%. The high response rate was accompanied by an overall very positive response by many electrical vehicle owners, who not only answered and returned the survey, but also sent e-mails (approx. 10 respondents) and called (approx. another 10 respondents) the authors to show their interest in the results as well as to further discuss their experiences with EVs.

The survey contained some questions with free text answers (e.g. average income) although the majority of the questions consisted of multiple-choice answers. In order to obtain additional information from them, in the end of the questionnaire, respondents were given the opportunity to write additional comments and suggestions related to the topic (not discussed in this paper).

Based on the targeted topic, the questions included in the survey could be divided into four different groups. The first group comprised questions regarding the drivers personal and household characteristics: age and gender, place of living, type of home (house or apartment), composition of the household (number of children, ages, etc.), educational levels of the household members and average income among others.

A second group of questions targeted the EV drivers motivation and use of their electric vehicle, for instance:

- Main reasons for purchasing the electric vehicle;
- Is the EV used as the main or as a secondary vehicle?;
- If they have an ICE vehicle, would they consider using only an EV in the near future?
- What is the main use of the EV? related to work, holidays, errands, etc.;
- level of satisfaction with their EV;
- The way EV drivers are currently paying for charging their vehicles and how would they like to be charged in the future.

Another set of questions looked to gather information on EV drivers driving and charging patterns: what is the approximate driving distance per day; what time of the day (divided in weekend and week days) is the electric vehicle charged; the typical place of charging the vehicle (e.g. at work, at home); what type of improvements would the drivers suggest in order to improve the current charging and EV infrastructure (e.g. longer driving range, more fast charging stations, etc.); among others.

A last group of questions targeted information about the technical specifications of the EVs as for example, the vehicles battery capacity. Due to this papers focusing on analyzing the characteristics of current EV owners, answers regarding the technical aspects of EVs have not been taken deeply into consideration.

2.2. EV charging impact on the grid

Using the same modelling framework presented in Ref. [45], a simulation model for a residential distribution system, where residential users are connected to a single low-voltage (400 V) feeder was developed. The general topology is presented in Fig. 1.

The models were built in the Dymola/Modelica simulation environment and validated with measured data. Modelica is an open source, object-oriented language for modelling physical systems. Its language is based on a causal modelling using mathematical equations and object-oriented constructs to facilitate the reuse of models in order to allow for effective library development and model exchanges [46].

Several EV adoption levels were simulated (0%, 30%,50%,70%, and 100%) in order to determine the impact of the different

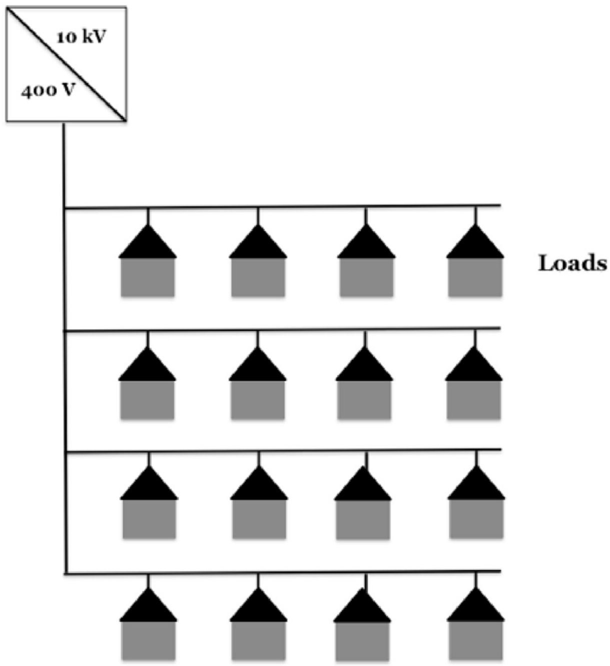

Fig. 1. Residential distribution grid topology.

amounts of EVs on the distribution grid. The initial state-of-charge (SOC) of the vehicles was defined to be 50% and they would all charge during nigh time. Additional simulations were carried out, that involved shifting the charging time by two-hours of different amount of vehicles.

3. Results and discussion

An important first step in the analysis of the responses is to evaluate the current stage of EV adoption of the survey participants. The respondents can be considered as early-adopters based on the still significantly low share of EVs in Sweden (less than 0.2% of the total share of passenger cars [47]). Additionally, most of the respondents were also new to the technology, according to the number of responses (N = 247) to the question For how long have you been using your electric vehicle?: 66% of the EV users have had their electric vehicle for a period of one year or less, 26% has used them for 1–2 years; while very few of the EV owners, 8%, had used this type of car for 3 years or more.

3.1. Socio-demographic characteristics

Starting with the gender of the survey respondents, out of the 247 respondents, 48 (19%) were female while 199 (81%) were male. Although the ratio between male and female is quite unbalanced, this result is not surprising since other studies have also identified male drivers to be among the typical early adopters of electric vehicles [36]; [48].

A frequency distribution of the age of the EV owners in Sweden that responded to the survey is presented in Fig. 2. The results indicate that most of the respondents are between 40 and 45 years of age. However, the resulting plot is a right-skewed distribution where the groups of 35 and 50 to 65 were almost equally represented and a lower and rather uniform distribution for the age groups of 35, 50, 55, 60 and 65 years old.

Results from previous studies indicate that early adopters of EV usually have high incomes, therefore, the survey included

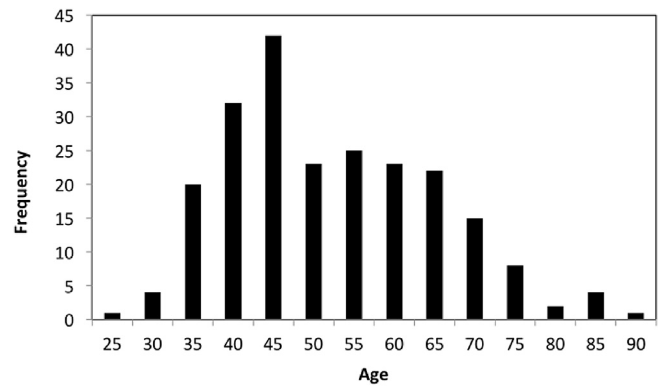

Fig. 2. Frequency distribution of the age of EV owners.

questions regarding the EV owners income levels. Responses were divided into three groups: lower than 50 000 SEK (approx. 5350 EUR); 50 000–100 000 SEK (approx. 10700 EUR); and above 100 000 SEK. The income-related responses indicate that the current EV owners in Sweden belong to the rather higher end since 53% of the respondents answered that their monthly salaries were between 50 000 100 000 SEK and 26% of the EV drivers had salaries of more than 100 000 SEK/month. The results are in line with findings from studies carried out in other countries [49]; [9]. Respondents were asked about the education levels of the household members above the age of 18; the number of people in the households with only a primary school education; with only high school degree; and with University degrees. Of all 247 respondents, 189 (76.5%) indicated to have a University degree showing a high level of education among the early adopters of EVs.

As seen in Fig. 3, current EV owners in Sweden live in 2-member families (35%) or families with 4 members (30%). The results showing that families with children use EVs are important for future marketing campaigns and focus groups, for instance, showing that families trust EVs to drive their children with, could increase the confidence among other potential EV owners.

With regards to the geographical distribution of the EV early adopters, the most densely populated counties in Sweden are the ones that comprise the majority of the EV drivers: Stockholm county (40%), Västra Götaland county (19%) and Skåne county (17%). However, very few of the participants stated to live within the largest cities: 8% of the EV drivers were located in Stockholm city; 2% in Gothenburg and 2% in Malmö [50].

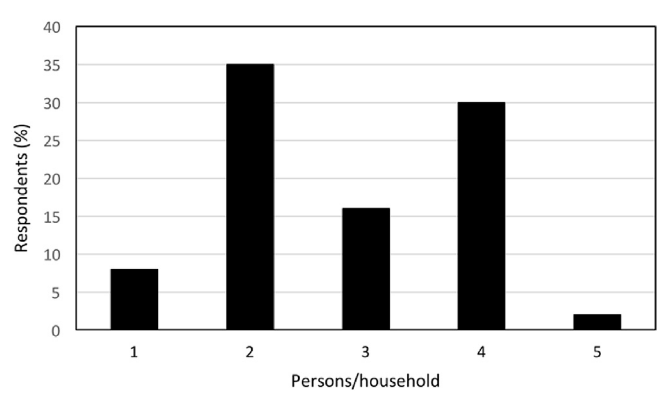

Fig. 3. Swedish EV owners household composition.

3.2. Motivation and the EVs use patterns

Personal believes and motivation factors have been identified as to have significant impact on the adoption intention [51]. In this section the early adopters motivation for choosing an electric vehicle as well as the main purpose of use have been identified.

In order to find out about the main use of EVs among early adopters, respondents were asked if they use their cars for private purposes or for work related matters. Of the total 247 respondents, 80% answered they use the electric vehicle only for private purposes; 1% responded that the cars are used for work related activities; and finally, 19% of the drivers use the EVs for both, work and private purposes.

Closely related to the main use of the EVs, is the total number of vehicles (including ICE vehicles) in the household. Out of the total 247 EV owners that participated in the survey, 36 (14.5%) stated to only have one vehicle in the household, being that vehicle electric. It is important to note that 15 of these 36 EV owners lived in apartments buildings. Usually, there is a limited number of parking places available for people living in multi-family buildings in Sweden, which might explain why the respondents only have one vehicle; all respondents with a total of 3 cars per household lived in houses. 139 (56%) EV owners responded to have two vehicles in the household, in 8 of these households (5.7%) both vehicles were electric. Among the respondents, there were 71 (28.7%) with 3 vehicles per household; 11 of which (15.5%) where 2 out of the 3 vehicles were electric. Moreover, out of the 210 respondents with more than one vehicle, 186 (88.6%) answered they "*would definitely consider using only an electric vehicle in the near future*".

In addition, the level of satisfaction among existing EV drivers has also been included in the survey, showing that 69% of the respondents (N = 242) are *very satisfied* with their EVs; 29% are *satisfied*; and only 1% are *not satisfied* or *not satisfied at all* (Fig. 4).

As indicated earlier, some studies have raised concerns related to the impacts of incentives, subsidies and policies benefiting EV buyers and users. Holtsmark et al. presented a thorough analysis of the EVs incentive and subsidy implications in Norway, discussing the changes in driving patterns before and after purchasing an EV, resulting in EVs substituting the use of public transportation in many of the cases [32]. Additionally, the subsidies and benefits for having an electric vehicle (e.g. using bus and collective lanes in cities; exemption from parking and charging fees) had mainly encouraged families with high income to purchase an electric vehicle and using it as a secondary vehicle. In order to analyze the situation in Sweden, EV owners were asked if they use their EV as a primary or as a secondary vehicle. Despite the relatively high rate of respondents having more than one car, 203 (82%) of the survey participants answered they use their electric vehicle as their primary vehicle. Moreover, when considering the 36 respondents that only have one car (and the car being electric), 23 of them stated that prior to buying the EV they only used a conventional vehicle as their main means of transportation while only 5 answered they used public transportation and/or bicycle/walking.

Since EV drivers in Sweden have been provided with too few incentives and benefits for owning an electric car, it is important to learn more about the motives behind purchasing and using this type of vehicles.

The question regarding the reasons for choosing an electric vehicle, included a multiple-choice answer, with several possibilities (*environment*, *cost-efficiency*, *safety*, *design*, incentives and *others*, where the respondents were given the possibility to specify other reasons that made them choose an EV). The results were classified based on the gender of the respondents and have been presented in Fig. 5. For both women and men (55% and 44% respectively) the lower impact that electric vehicles cause on the environment was the most attractive motive for purchasing this type of vehicle.

The cost-efficiency of electric vehicles was the second reason for purchasing this type of vehicle, with 34% of male respondents and 25% of female EV owners selecting that option. The *cost-efficiency* of the electric vehicles refers to their charging costs and other costs associated to its maintenance. In the option *others*, 30% of the respondents that chose this option, specified that what attracted them the most to electric vehicles was that they were considered as *new*, *exciting* and *interesting* technology.

It is important to note the similarity in the selection of the reasons for purchasing an EV between male and female respondents, showing the results that despite the low number of female EV drivers, in comparison to males, overall they have the same motivations for choosing this type of vehicle.

Furthermore, the impact of the age of the participants on the decision for choosing an electric vehicle was investigated. Age groups with a number of respondents lower than 5 were excluded from the analysis, since the results from those age groups were not considered to be representative.

As presented in Fig. 6, the *environment* and *cost-efficiency* of the EVs were clearly the strongest motivating factors for using an EV across all age groups. The main differences are observed in the groups between 26 and 40 years old, where *cost-efficiency* is the predominant reason for choosing an EV, shifting towards

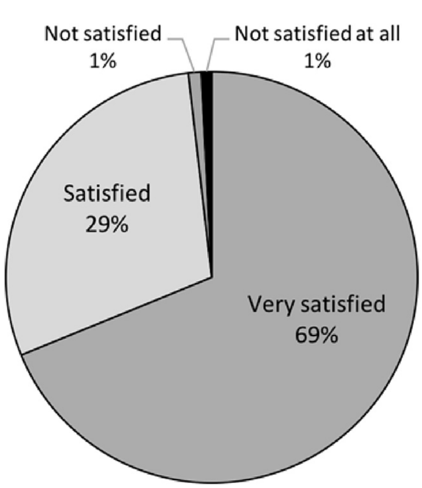

Fig. 4. Satisfaction level of EV owners with their cars (n = 242).

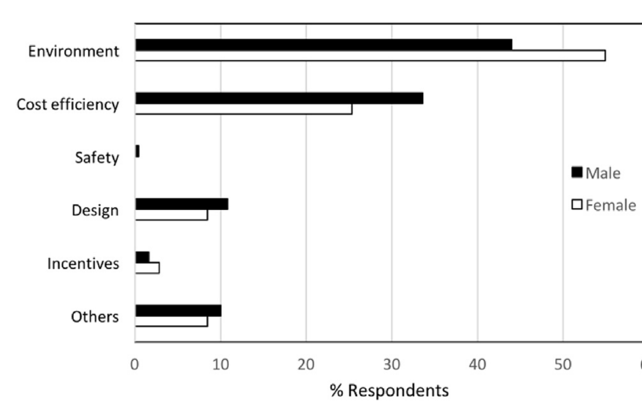

Fig. 5. Main reasons for choosing an electric vehicle, based on gender distribution (N = 247).

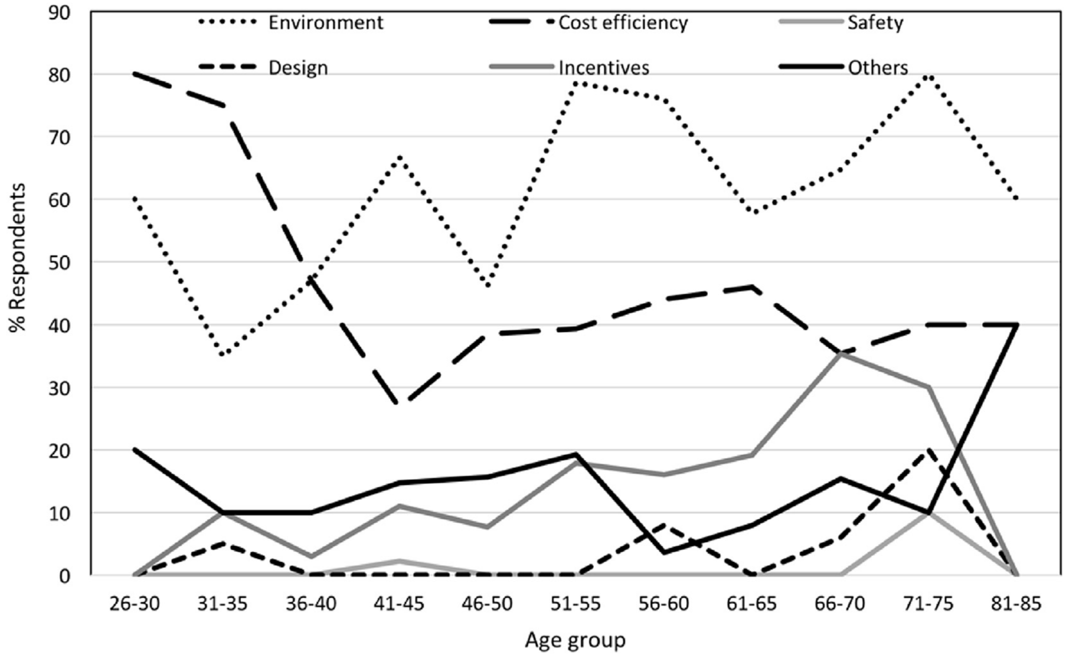

Fig. 6. Main reasons for choosing an electric vehicle, based on the respondents age (N = 243).

environment for the rest of age groups. The overall low electricity prices in Sweden [52] make electric vehicles very attractive, especially to the younger groups with relatively low income (50 123 SEK/household as average for the group 26–35). Less than 20% of the respondents in all age-groups, selected any of the other provided reasons (*design*, *incentives*, *safety*, *others*). Surprisingly, the group with the highest percentage of respondents (20%) that chose *design* of the car as one of the reasons for choosing an electric vehicle, was the group of 71–75 year old, where all other age groups show a very low interest in the design of the vehicles (see Fig. 6).

3.3. Driving and charging patterns

Understanding different driving and charging behaviors provides important insights for urban planners and grid operators to improve the spatial planning of public charging points [53], especially in densely populated urban areas, and to improve *vehicle-to-grid* and scheduled recharging strategies and facilitate grid stability issues [44]. As presented earlier, the majority of the EV owners live in houses outside densely populated areas, and one of the reasons for this is the lack of charging infrastructure within the city perimeter. Additionally, in Sweden, there is a lack of general support for charging points besides the funding provided for R&D [31]. Analyzing existing charging locations and the time of the day when the electric vehicles are charged plays an important role in the preparation for scenarios with large numbers of EV market penetration. In the case of commercial fleet EVs, the charging patterns are more predictable and usually occur at the work place. As an example, a study carried out in Australia [54] concluded that the energy used for charging peaked between 8 a.m. and 10 a.m. as vehicles arrived to work and that the average distance before charging was way below the maximum range of the vehicle with 83% of charge events occurring when the vehicle still had more than half of its maximum allowable range remaining. In Europe, a survey carried out by Young et al., showed that 60% of drivers in Europe, despite driving less than 160 km a day, would not consider a driving range of less than 160 km as acceptable [55]. The survey participants analyzed in this study were asked to indicate the approximate daily distance driven with their electric vehicles. Three different distance intervals were suggested: less than 30 km/day; between 30 and 100 km/day; and 100 or more km/day (Fig. 7).

As presented in Fig. 7, the majority of the respondents (64%) answered that they drive their electric vehicle for distances between 30100 km/day. These findings are important to consider when providing potential EV owners with information and help reduce *range anxiety* and dispel the misconception about existing battery technology being insufficient for daily EV use.

Regarding the most commonly used charging location, 173 (70%) of the EV owners stated they only charge their vehicles at home; while 12 (5%) use the charging spots at their work places. Only 1% of the respondents charge their vehicles while doing errands. Additionally, 15% of the EV owners indicated that they charge their vehicles wherever they can: at home, at work and while doing errands.

In order to learn more about the charging routines of current EV owners, participants were asked to respond about the time of the day they usually charge their vehicles. The question was divided

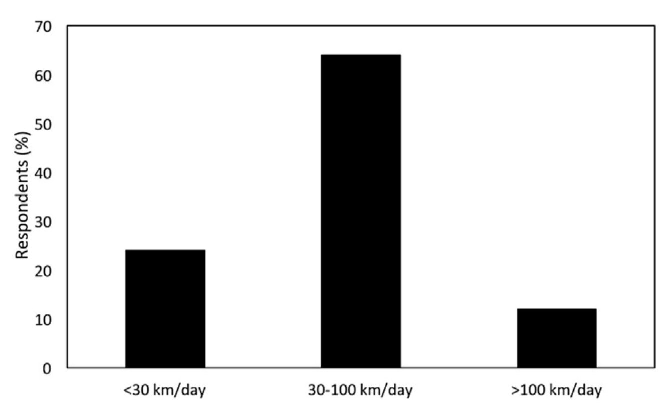

Fig. 7. Approximate kilometers per day driven by EV owners in Sweden (N = 245).

into two parts, one targeting the charging patterns during weekdays and another focused on the weekend days.

The results presented in Figs. 8 and 9 indicate that the majority of the EV owners charge their cars during night hours; 57% during weekdays, and 62% during weekend days.

When comparing the charging activities carried out during the weekdays and weekend days, there are no major differences observed between the different days in both cases-, charging occurs mainly at night, followed by evenings (21% during weekdays and 20% during weekend days). Additionally, the fact that most participants do not use their electric vehicles for work but rather for private purposes (80% of the respondents), and also that vehicles are usually charged at home (70%), provide important insights that could be used for future regulations that focus on the profits share for the vehicle owners for allowing their cars to be part of controlling agreements. Also, based on the existing charging habits, if current trends continue, even among future EV drivers and in densely populated urban areas, it is important to develop different load-shifting strategies with charging schedules, in order to avoid overload the electric grid during the evening peak period.

3.4. EV penetration impact on power distribution systems

As mentioned before, large penetration of EVs can impact the performance of existing distribution infrastructure. If all existing EVs that are connected to the grid in Sweden are taken into account (both private and for commercial/corporate use), the number will reach approximately 14 000 at the end of 2015 [13]. Furthermore, in order to meet Sweden's fossil-independent transport system by 2030, a significant increase of EVs on the system can be expected [56]. According to the Swedish Energy Agency, based on today's and expected future incentives, the combined number of BEVs and PHEVs could reach 650 000 in 2030 (about 15% of today's number of passenger cars in Sweden), out of which at least 25% would be BEVs [57].

While the overall electricity consumption increase could be met by Sweden's generation capacity projections of 175 TWh by 2030 [56], the increased number of EVs can severely affect today's power consumption profile by increasing the evening peak, when, according to the survey carried out in this paper, is when customers are more likely to charge their vehicles. This peak increase, in

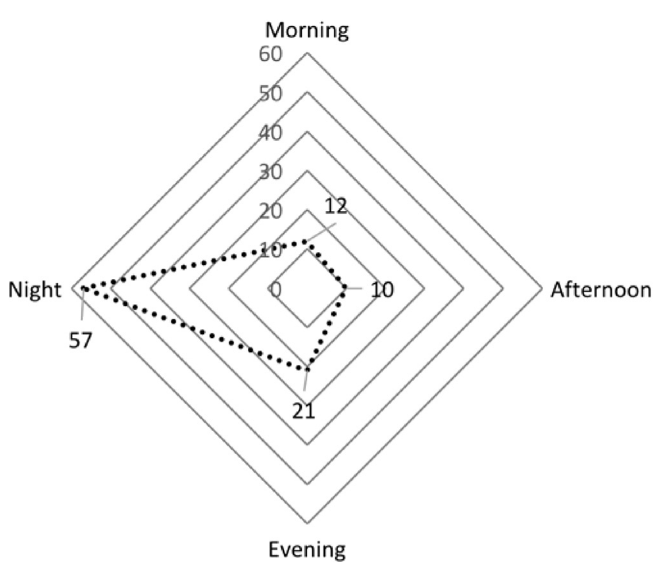

Fig. 8. Time of the day when EV owners typically charge their cars during weekdays (n = 247).

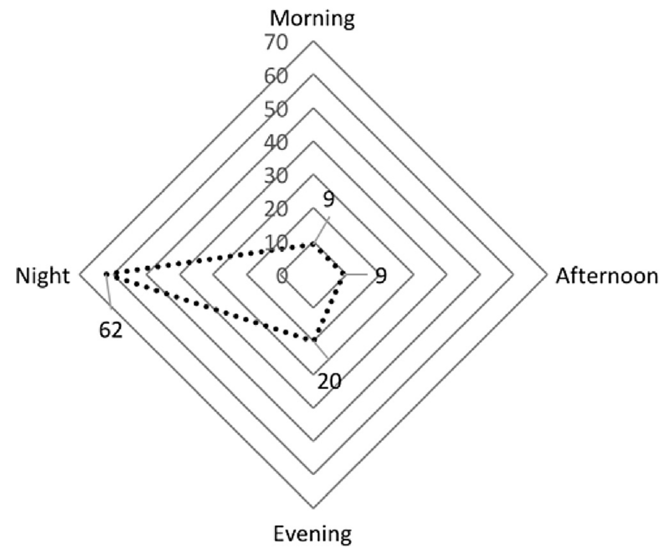

Fig. 9. Time of the day when EV owners typically charge their cars weekend days (n = 235).

combination with today's available variable pricing schemes (real-time pricing and demand-based pricing) could lead to a system peak that requires the use of fossil-fueled peak power stations. The use of these peak power stations increases the CO_2/kWh in the electricity mix, and in consequence, the running cost per km of EVs due to an increased system's electricity price.

This effect of random uncoordinated EV charging was analyzed in depth by Masoum et al., where a simulation was carried out in a 1200 node test system topology that consisted of several low-voltage residential networks with different levels of EV penetration [37]. Results showed that without coordinated or scheduled charging, voltage violations would occur during the night-peak with penetrations as low as 17%. Furthermore, a simulated EV penetration of 62% (the maximum penetration simulated) would increase total distribution losses by 500%.

Similar results were obtained for the small distribution system model built for Sweden. With uncoordinated charging EV penetrations over 30%, voltage violations occurred and distribution losses increased significantly. As observed in Fig. 10, similarly to the results presented by Masoum et al., simulation results also determined that scheduled charging would be required in order to allow for large penetration of EVs, without requiring significant upgrades on the existing infrastructure [37]. The charging starting time was

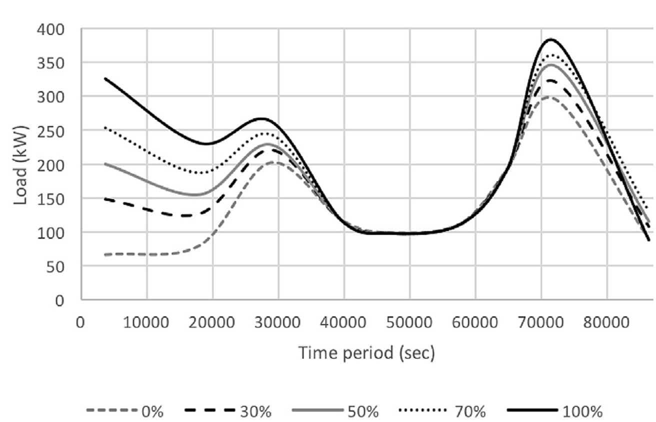

Fig. 10. Load increase with different levels of EV penetration.

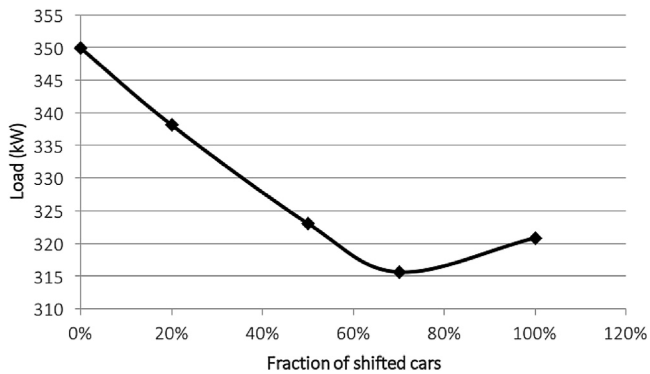

Fig. 11. Impact of charge scheduling.

shifted two hours away from the nightly (20:00) peak and helped decreased it significantly, however, shifting a large share of EVs (>60%) would create another peak at a different time, which is also an undesired effect. Results are shown in Fig. 11. Additional simulations are presented in Ref. [58].

Coordinated smart charging would be necessary in order to allow for a large penetration of EVs without introducing severe disturbances on the existing distribution grid, but more importantly, this controlled charging scheme would also benefit the integration of renewable energy sources by maximizing its self-consumption of electricity (e.g. Solar PV-covered parking lots for charging EVs during daytime) and providing with energy storage for load balancing purposes using V2G schemes. Fortunately, coordinated smart charging would use the already existing smart metering infrastructure to obtain real-time information about the capacity of the distribution grid. In addition, this system would use the mature mobile network as the central communication backbone, to send and receive information to and from the electric network operator about when to start and stop charging the EVs. While it would be ideal for the system to work autonomously in a plug-and-forget way, customers would still have the option of *forcing* start charging their EVs when they need to, however, if this is done during high-peak periods, customers would have to pay a *premium* cost for electricity.

4. Conclusions

While there are still uncertainties on how to integrate EVs with the existing urban, electrical and transport infrastructures in the most sustainable and suitable way, their use has still experienced a steady growth. Sweden has many features that make the country suitable for a large-scale penetration of EVs, for instance, its large share of renewable energy sources and its citizens high environmental awareness. The lack of strong incentive programs and other market penetration barriers have, however, resulted in the country lagging behind other similar nations in the number of EVs on the road. In order to help tackle market penetration barriers and to use current trends to analyze the potential impact on the distribution grid, a survey to all private EV owner was used as a way of gathering information form EV early-adopters. The questions included in the survey were aiming at gathering information regarding current EV owners socio-demographic characteristics, preferences, reasons for choosing an EV, satisfaction level and driving and charging patterns, among other information.

The results characterize the typical EV owner in Sweden as male, with medium-high income; highly educated; living in a 2 or 4-member family and in houses usually located in areas with low population density. The main use of the EVs is for private purposes, and although usually owning a second car, EVs are used as the primary vehicle. EV owners are very satisfied or satisfied with their electric car and the majority would consider using only electric vehicles in the near future. No major differences were found between female and male EV owners, regarding their motivation for choosing an electric car, for both gender groups, environment and cost efficiency were the main reasons selected. The identified characteristics of current EV owners should serve to other countries with similar conditions and in their initial stage of implementation, to know what to expect in terms of early adopters.

The current distances driven by Swedish EV owners (between 30 and 100 km/day) and the charging occurring at night and mainly at home, could be used as a valid argument to help reduce the range anxiety considered as a major barrier to mass adoption of EVs. Additionally, based on the insights provided in this study regarding the place and time of the day charging, the results from the simulation model suggested that controlled charging schemes should be adopted in order to allow high EV penetration levels on local distribution networks. Moreover, it was found that load-shifting strategies should be developed in order to prevent overload the electric grids during evening peak hours, when most EV drivers come home and plug their vehicles to charge. In order to achieve a sustainable use of EVs, national and local governments should focus on providing support for the planning of location of charging stations in densely populated areas, e.g. slow charging stations should be located in parking garages and areas close to the drivers homes where the cars can be left charging at night.

The results regarding the EV owners experiences and levels of satisfaction presented in this study can be used to promote the use of EVs to other drivers as well as to further improve the driving experience of current EV drivers as well as to improve the chargers design and update the communication systems of today's distribution systems, in order to allow for controlled scheduled charging for EVs.

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