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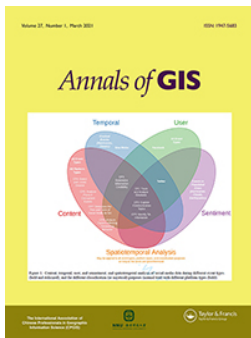
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Drivers' range anxiety and cost of new EV chargers in Amsterdam: a scenario-based optimization approach

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ABSTRACT

Due to the sharp growth in the adaptation of electric vehicles (EV) in the Netherlands and the objectives of the Dutch Climate Accord is to encourage electric mobility, in the coming decades a substantial number of new EV charging facilities needs to be provided. Efficient planning of EV charging infrastructure is coupled with the notion of range anxiety, which is likely to be severely high in case of soon-to-be EV drivers. This study aims to estimate the cost of developing a new charging infrastructure under five scenarios of range anxiety in Amsterdam East. Employing a Linear Integer Programming optimization model, on the basis of geographic data on car registration, existing EV chargers, and electricity substations, it is obtained that if drivers use 90% of their battery before using a charging facility, the existing charging infrastructure needs to be expanded by only 31% to accommodate almost seven times larger number of EVs – the threshold set by the European Union (EU) legislation on the deployment of alternative fuel infrastructure. If drivers use only 30% of the batteries; however, an increase of 167% in infrastructure is inevitable (accounting for almost five million euro of cost). Second, at any point along the range anxiety spectrum, if the interval between charging session increases for 1 day, the overall cost decreases by more than 30%. These findings are discussed, and two policy approaches are proposed: (1) information technology approach; (2) demand-response approach, on the basis of EU legislation on energy efficiency and deployment of alternative fuel infrastructure.

1. Introduction

1.1. Upcoming demand for electric vehicle charging infrastructure and potential impact of range anxiety

The number of electric vehicles (EV) is sharply increasing. In 2017, 1.8% of the total cars sold in the European Union (EU) and the European-Free Trade Association (EFTA) member states were electric, compared to virtually zero in 2010 (Tsakalidis and Thiel 2018). EV market share around the globe is projected to enlarge to 20% in 2030 when the annual sale of EVs will reach to 3.5 million vehicles per year (Edison Electric Institute 2018). In the Netherlands, in June and July 2018, the share of EVs among new-registered cars has reached almost 10% (Netherlands Enterprise Agency 2018). The aspiration of the Dutch climate accord is to increase the share to 100% by 2030 and to achieve a fully zero-carbon mobility system by 2050 (Ministry of Economic Affairs and Climate Policy 2019).

In the coming decades, a substantial number of new EV charging facilities needs to be provided. Edison Electric Institute estimates that by 2030 about 9.6 million new EV chargers need to be allocated around the globe (Edison Electric Institute 2018). The European Parliament's Directive 2014/94/EU on the deployment of alternative fuel infrastructure urges the member states to provide 'at least one recharging point per 10 cars' (Official Journal of the European Union 2014; pp. L. 307/4). The need for new EV charging infrastructure is particularly urgent in the Netherlands as the ratio of EVs to public chargers is the fourth highest among the member states of EU and EFTA (Tsakalidis and Thiel 2018). This urgency is underlined in the Dutch policy documents. The Electric Transport Green Deal 2016–2020 set its first goal as 'Improving and expanding the charging infrastructure for EVs' (Government of the Netherlands 2015, 4). The Dutch Climate Accord set the provision of EV charging infrastructure by 2025 as one of its goals and emphasizes the need for spatial plans with a focus on transport infrastructure in three major

metropolitan regions, among them Amsterdam Metropolitan Area (Ministry of Economic Affairs and Climate Policy 2019).

Efficient planning of EV charging infrastructure is coupled with a variety of consumer behaviours, among them range anxiety. Range anxiety refers to drivers' fear of being stranded with an out-of-charge vehicle before reaching their destinations or the closest available charging station (Tate, Harpster, and Savagian 2008). Highly range-anxious drivers could make night-time use of charging facilities highly inefficient. If and when an EV is plugged to a charger in the early evening, the charger could not be used by other EVs for the rest of night. Range-anxious drivers might occupy a spot for charging a small portion of their battery lasting for a short period of time, and, in effect, keep a substantial portion of charging capacity unused for the rest of the night. This could make the planning of EV infrastructure in the Netherlands quite difficult, as most of the future EV drivers would have little or no experience with the use of EVs. Previous studies show that inexperienced EV drivers are likely to be more range-anxious than drivers with longer experience of using EVs (Rauh, Franke, and Krems 2015).

This study aims at estimating the cost of developing a new charging infrastructure for a real case study in the city of Amsterdam under different scenarios of range anxiety. It determines the extent to which the costs could be reduced if and when drivers become less range-anxious, and what portion of resources could be spent on the reduction of range anxiety. The results of this study contribute to the elaboration of policies for further development of EV infrastructure in the city of Amsterdam and set an approach applicable to other cities. In the next part, previous studies are briefly reviewed and a knowledge gap in these studies is identified. Subsequently, the aim and approach of the study, data and case study, as well as the method are described. In the two final sections, the results are presented and discussed, a set of possible policy implications are suggested, and further studies are proposed.

1.2. Previous studies and knowledge gap

In order to optimally allocate EV chargers, a variety of methods has been previously employed. Linear Programming (LP) is perhaps the most simple and commonly used methods. Franco, Rider, and Romero (2015), for instance, found the minimized solution for a problem on EVs' energy use utilizing mixed-integer linear programming (MILP). Nonlinear formulations are previously employed, too. Sadeghi-Barzani, Rajabi-Ghahnavieh, and Kazemi-Karegar (2014), for instance, have employed a

mixed-integer nonlinear optimization for allocation of mega charging stations at the metropolitan scale. Genetic Algorithm (GA) is previously used to solve large-size problems. Tong et al. (2014), for instance, have solved a multi-objective problem of the allocation of PHEVs' charging stations by the use of GA. Ant Colony Algorithms (ACO) has been previously employed to optimize EV fleet. Yang et al. (2014), for instance, have employed AOC to optimize the spatiotemporal performance of EV charging loads. Ultimately, Particle Swarm optimization has been previously employed for solving problems such as vehicle-to-grid optimization (Saber and Venayagamoorthy 2009).

According to their approach to range anxiety, the previous studies on the optimal allocation of EV charging stations could be categorized into four types. The first type, accounting for most of the studies, has acknowledged the impact of range anxiety on the outcome of their models; however, they have approached the issue only by assuming a fixed value or a stochastic function. This group of studies does not offer a calculation regarding how altering range anxiety would affect the results. Ahn and Yeo, for instance, developed a comprehensive model of Estimating the Required Density of EV Charging (ERDEC) at a minimum cost with regard to a variety of technological and regional parameters. The model, however, 'provide[s] the optimal number of chargers for driving without driving-range anxiety' (2015, 1). Planning electric vehicle charging infrastructure for the Italian highway network, Micari et al. (2017) fixed the level of range anxiety at 75%. A study on the association between the walkability of urban areas and the cost of electric vehicles' fast chargers set the level of range anxiety at 70% (Mashhoodi et al., 2019). Alhazmi, Mostafa, and Salama (2017) have acknowledged the significance and uncertainty of the 'remaining electric range' of the EVs and adopted a stochastic function to accommodate it. Dong, Liu, and Lin (2014) analysed the impact of the availability of public chargers on the total travel distance of EV drivers, who are assumed to have a fixed driving range.

The second type of studies elaborated on the financial costs of range anxiety for EV owners and drivers but neglected the costs this imposes on cities, which need to provide the chargers. Lin (2012), for instance, conducted a detailed calculation of range anxiety cost for EV owners, as the sum of the costs of vehicle substitution, emergency service, and detouring for a charger station. The study, however, remained short of calculating the cost of range anxiety for a city, i.e., the extra resources needed for the allocation of a more-than-necessary number of chargers. Neubauer and Wood (2014) approached the cost of range anxiety for households

from the perspective of a lifetime of EV batteries. The authors concluded that range anxiety could have a profound impact on reducing the lifetime of the batteries.

The third type of studies included 'driving range', which could indirectly be interpreted as a proxy for range anxiety, as a parameter of their models. These studies illustrate that range anxiety has a profound impact on the location and cost of new EV chargers. He et al. (2018) developed a bi-level programming model to maximizes the flow passing through the streets with chargers, at the upper level, and constrains the model with drivers' route choice and driving range, at the lower level. Searching for optimal locations of a predefined number of chargers, the results showed that driving range has a profound impact on the location of chargers. The study, however, fell short of estimating what are the necessary number of chargers, what is their cost, and how driving range may affect that. The result of the study conducted by Davidov and Pantoš (2017) could be indirectly used for estimating the impact of range anxiety on the cost of infrastructure. The authors used the range limitation of EVs as one of the parameters of their model, which could alternatively be interpreted as the range after which a driver charges her/his vehicle. The results show that in return for a 2.5 times increase in the range, the cost of infrastructure drops more than 70%.

The fourth type of studies included the few studies which accounted for range anxiety. By a study titled as 'The battery charging station location problem: Impact of users' range anxiety and distance convenience', Guo, Yang, and Lu (2018) acknowledged that mass adaptation of EV infrastructure is not possible unless the behavioural and psychological dimensions of uses are taken into account. The authors considered range anxiety and distance deviation as the two major obstacles in this regard. By defining different types of range-anxious drivers with various thresholds of anxiety, as well as considering different scenarios of battery range, the authors show that if and when range anxiety increases from 10% to 50% the overall cost of EV infrastructure can increase up to one-third. Xu, Yang, and Wang (2020), by a study titled 'Mitigate the range anxiety: Siting battery charging stations for electric vehicle drivers', have taken an innovative approach towards the range anxiety. The authors have searched for the optimal number of EV chargers that minimizes accumulated range anxiety of drivers, constrained by the total amount of available budget and subjected to detailed formulations of the detour and charging behaviours of drivers. By developing a compact model with polynomial constraints for the

very first time, the authors modelled the possibility that ranges anxious drivers took a short path to a refuelling station and mapped the curve of range anxiety against the state of charge of batteries. The model, consequently, is applied for a variety of OD pairs in a 25-nodes real-life highway network in Texas.

A knowledge gap exists in the current body of literature on range anxiety and the cost of EV-charging infrastructure: there is no comprehensive study available which offers a realistic estimation of the total cost of new chargers under different scenarios of range anxiety for a high-density inner-city area. The knowledge gap is particularly eminent in the case of Dutch cities which aim for further adaptation of EV mobility, among them Amsterdam.

1.3. Objective and approach of this study

This study aims to estimate the cost of optimal allocation of new EV charging infrastructure under different scenarios of range anxiety and to measure to what extent the overall cost could be reduced in return for alleviating range anxiety of EV drivers. This study is undertaken on the basis of seven principles, in accordance with the Directive 2014/94/EU of the European Parliament on the deployment of alternative fuel infrastructure (Official Journal of the European Union 2014):

Principle 1. highly-urbanized, mixed-use areas need to be prioritized for allocation of new charging infrastructure (in accordance with Article 2);

Principle 2. the new EV infrastructure must suffice to meet the demand under the scenario that one out of every 10 cars is an EV (in accordance with Article 23);

Principle 3. existing charging facilities need to be included in planning of new infrastructure (in accordance with Article 24);

Principle 4. allocation of chargers with multiple plugins is permitted (in accordance with Article 33);

Principle 5. the connection between EV infrastructure and the electricity grid needs to be taken into account (in accordance with Article 30);

Principle 6. Charging infrastructure needs to serve both residents and visitors of the neighbourhoods (in accordance with Article 26);

Principle 7. through registration cards and subscriptions, authorities can regulate charging hours of residents and visitors of neighbourhoods (in accordance with Article 26).

The study is carried out in a central, dense area of Amsterdam, in the Netherlands (*Principle 1*), based on GIS data on registered residential cars (*Principle 2*) and the existing publicly accessible EV chargers (*Principle 3*). The study aims to allocate semi-fast chargers (Level II) with five plugins (*Principle 4*) with a direct connection to electricity substations (*Principle 5*). In this study, the chargers to be allocated to meet residents' demand in course of nights, 8 PM-6 AM, and will be available for visitors between 6 AM and 8 PM (*Principle 6* and *Principle 7*).

2. Data and case study area

2.1. Common EVs in the Netherlands and the potential use of semi-fast chargers

To set the assumptions regarding average EVs' battery capacity, maximum driving range, and electricity consumption per kilometre, the data on the most common BEVs sold in 2018 in the Netherlands are used

Table 1. The most common BEVs sold in 2018 in the Netherlands.

|	Battery [kWh]	EPA Driving range [km]	Wh/km
Tesla Model S	90	426	211
Nissan Leaf	30	172	174
Tesla Model X	100	475	210
Renault ZOE	41	300	137
Volkswagen Golf	36	201	179
Jaguar I-Pace	90	377	239
BMW I3	33	183	180
Hyundai Ioniq	28	200	140
Opel Ampera	18.4	85	216
Smart Fortwo	16.7	108	155

(Rijksdienst voor Ondernemend Nederland 2019). The values are, respectively, set to 48.3 kWh, 252.7 km and 191.1 Wh/km (Table 1).

On average, a car in the Netherlands travels for 13,000 km per year (CBS 2016). Given the average electricity consumption per kilometre of common Dutch EVs, this implies that every EV consumes 6806 Wh per day. In this respect, if EVs are plugged into semi-fast chargers of 22 kWh capacity, one charger is sufficient to charge five EVs overnight, i.e., 8 PM to 6 AM. During the day, that is 6 AM to 8 PM, by using only one of the plugins, the charger could serve visitors of the neighbourhood for semi-fast charging, i.e., full recharge of an EV within roughly 2 h (Figure 1).
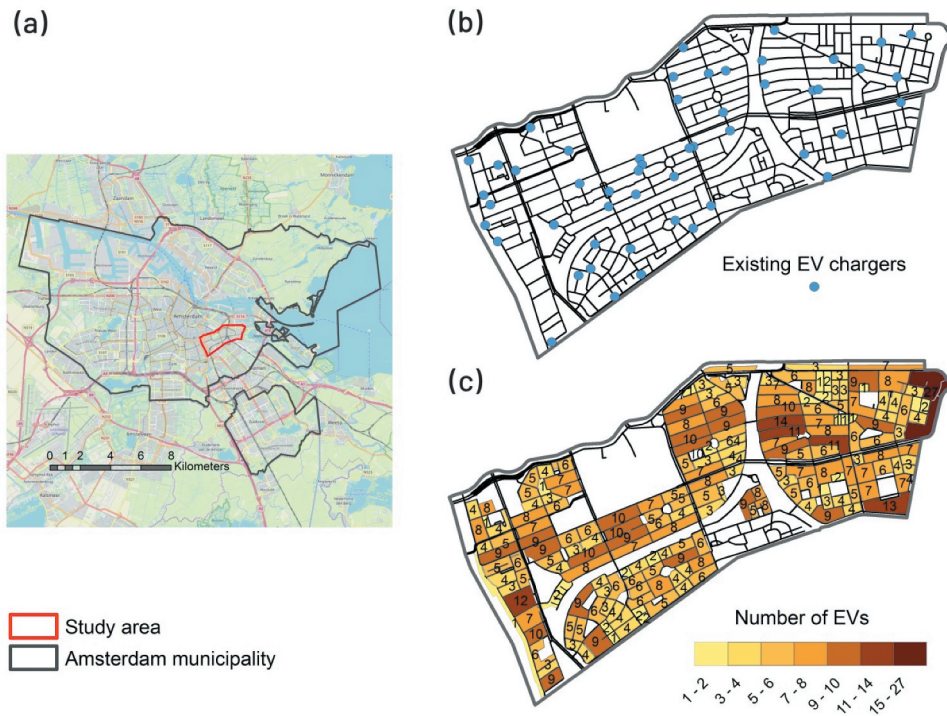
2.2. Case study area

Located directly adjacent to Amsterdam's historical city centre, the area studied in this experiment is densely populated and is highly mix-use (Figure 2a). The population of the area is almost 60,000 inhabitants (roughly 7% of The Amsterdam population) and the population density exceeds 20,000 inhabitants per square kilometre. In 2017, almost 6% of the businesses in Amsterdam were registered in the study area, among them more than 1000 hotels, cafes, restaurants, and more than 1800 businesses in culture and recreation sector. The study area is also home to one of the central buildings of the municipality of Amsterdam and a hospital (CBS 2017).

According to the interactive website of the EV chargers in the Netherlands (Oplaadpunten 2019), currently, 51 publicly available EV chargers are located in the study area. The capacity of the chargers is 11 kWh, and each of the chargers has two plugins (Figure 2b). The future number of EVs in the urban blocks of the study area, that is set as 10% of the existing number of residential cars (see subchapter 1.3), is estimated based on two

(a)   (b)
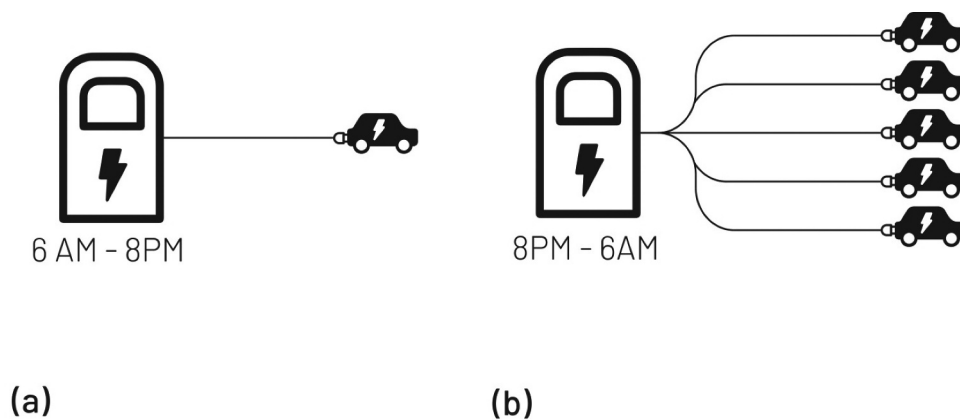
Figure 1. Use of a semi-fast charger station in day, by visitors of the neighbourhood, (a) and night, by neighbourhoods' residents – the basis for analysis in this study (b).

Figure 2. Case study area (a), location of existing publicly accessible chargers (b), expected number of EVs, that is equal to 10% of the number currently registered cars (c).

datasets: first, the number of private cars in the 17 subdivisions, so-called *buurt*, which comprises the study area, retrieved from GIS database of Dutch central bureau of statistics (CBS 2017); second, gross floor area of the building retrieved from Dutch 3D GIS database of buildings (Esri Netherlands 2015). To do so, it is assumed that EVs in each subdivision are distributed proportionally to the gross floor area of the blocks (Figure 2c).

2.3. Candidate locations for allocation of new chargers and costs estimation

To instal new charging points, 180 candidate locations are designated. The locations are selected with regard to the location of existing medium-voltage electricity substations. (Note that due to the conditions set by the provider of data, Alliander, the energy provider company of Amsterdam, the authors are obliged to keep the map of substations confidential.) The underlying principle for the selection is that as EV charger points impose a high pressure on the existing electricity grid, every new charger needs to be directly connected to an electricity substation by a new underground cable. By the choice of the candidate locations it is ensured that: (1) the closest locations to the substations are chosen; (2) every block has at least one candidate location within

200 metres walking distance; (3) between every two candidate locations there is enough space for 10 parking spots, set as 65 metres. The cost of establishing a new charger at each of the candidates location as calculated as below:

$$C_j = (L_1 + L_2)C_1 + C_2 + 5C_3 \tag{1}$$

where C_j denotes the cost of a new charger station at candidate location j. L_1 is the length of the necessary underground cable from the closet substation to the centre of its closet street, and L_2 is the length of underground cable under the street (Figure 3a). C_1 is the cost of laying underground cable per metre. In general, estimation of and collecting data on the cost of underground construction is troublesome, as most of the contractors are privately owned companies who do not disclose their tariffs (Romero and Stolz 2002). Following an estimation provided by the U.S. department of energy, in this study the cost of underground construction is considered as 1200 euros per metre (Warwick et al. 2016). On the basis of a guideline by the U.S. department of energy (Smith and Castellano 2015), C_2, the cost of a Type II charger with 22 kWh capacity, is set as 6500 euros, and C_3, the cost of each of the five cords and connectors of plugins is set as 1500 euros (Figure 3b). These cost add up to the total cost of establishing a new EV charger at each of the candidates location (Figure 3c).

Figure 3. The cost of a new semi-fast charger at a candidate location account for cost of cabling to electricity substation (a) and cost of a semi-fast charger with 5 plugins (b). The overall cost is calculated and mapped for each of the 180 candidate locations (c).

3. Method

The optimization model of this study is a linear integer programming problem with the objective function of minimizing the total cost of establishing new charging infrastructure (equation 2). The feasible solution of the models is restrained by three types of constraints. The first set of constraints ensures that: (1) the demand for EV charging in all the blocks are allocated to a new or existing charger, and (2) distances between the blocks and those chargers do not exceed a 200 m walking distance (equation 3). The second set of constraints controls that the total number of EVs assigned to a new charger does not outnumber its capacity (equation 4). Every new charging can simultaneously charge five EVs between 8 PM and 6 AM. Given that every EV consumes 15% of the capacity of its battery every day, the daily interval between the charging session of an EV is $R/0.15$, where R denote range anxiety, i.e., the percentage of battery which is empty when a driver plugs an EV into a charger. In this respect, every new charger can be assigned to $5\,R/0.15$ EVs. The third set of constraints limits the number of EVs assigned to the existing chargers to their capacity (equation 5). The existing chargers in the study area have two plugins. The total capacity of an existing charger, in this respect, is $2\,R/0.15$.

$$\text{Minimize} \sum_j C_j y_j \qquad (2)$$

$$\text{Subject to}: \sum_j x_{ij} d_{ij} + \sum_z n_{iz} \gamma_{iz} = EV_i \qquad (3)$$

$$\sum_i x_{ij} \leq 5Ry_j/0.15 \qquad (4)$$

$$\sum_i n_{ij} \leq 2R/0.15 \qquad (5)$$

$$x_{ij} \in \{0, EV_i\}$$

$$n_{iz} \in \{0, EV_i\}$$

$$d_{ij} \in \{0, 1\}$$

$$\gamma_{iz} \in \{0, 1\}$$

$$x_{ij}, d_{ij}, n_{iz}, \gamma_{iz} : integer$$

Below the parameters of the model are explained:

$C_j =$ cost of establishing a new charger at the candidate location j

$$y_j = \begin{cases} 1, & \text{anew charger is located at the candidate location } j \\ 0, & \text{otherwise} \end{cases}$$

x_{ij}: number of EVs of block i that use the new charger located at the candidate location j

Table 2. The five scenarios of range anxiety.

Range anxiety(frequency of charging)				
90% (6 days)	75% (5 days)	60% (4 days)	45% (3 days)	30% (2 days)
SC#01	SC#02	SC#03	SC#04	SC#05

$$d_{ij} = \begin{cases} 1, & candidate\ location\ j\ is\ within\ 200\ meters \\ & walking\ distance\ from\ block\ i \\ 0, & otherwise \end{cases}$$

n_{iz} : number of EVs of block i that use the existing charger located at z

$$\gamma_{iz} = \begin{cases} 1, & existing\ charger\ z\ is\ within\ 200\ meteres \\ & walking\ distance\ from\ block\ i \\ 0, & otherwise \end{cases}$$

EV_i = total number of EVs in block i

R = range anxiety, i.e., the percentage of battery which is empty when a driver plugs an EV to a charger.

To estimate the impact of range anxiety on the total cost of developing the EV infrastructure, optimal solutions for five scenarios of range anxiety are calculated (Table 2). To find the optimal solutions, the MATLAB's Mixed-Integer Linear Programming plugin (MathWorks 2019) is utilized. The optimization method is set as a branch and bound.
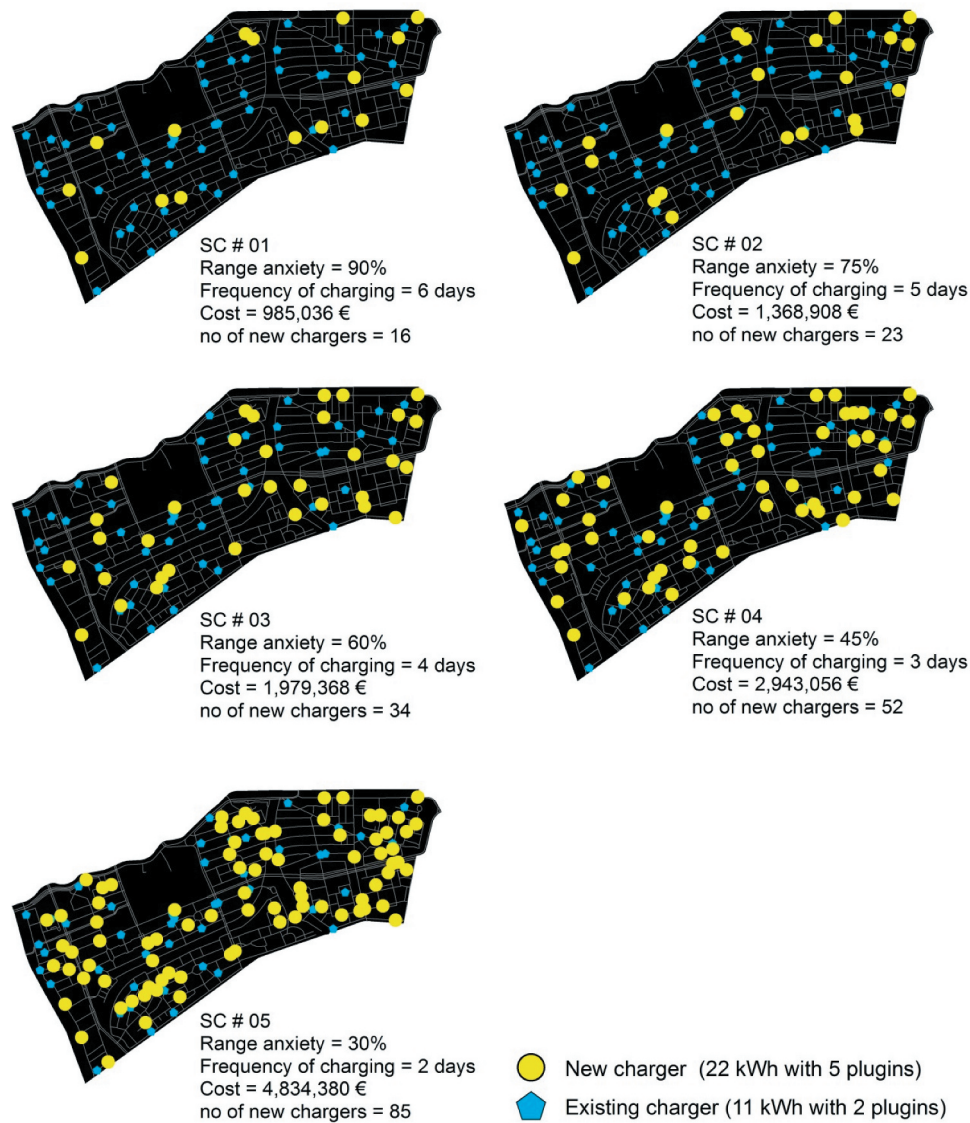
4. Results

The result of the optimization models shows that to meet future demands, under different scenarios of range anxiety, between 16 and 85 new chargers are needed, in addition to the existing 51 public chargers. This indicates that if drivers use 90% of their battery before using a charging facility, the existing charging infrastructure needs to be expanded by only 31% to accommodate almost seven times as many EVs. If the range anxiety is as high as 30%, an increase of 167% in infrastructure is inevitable. It is found that there is a nonlinear relation between range anxiety and the number of necessary chargers. For instance, a comparison between the optimal solutions of SC#01 and SC#05 shows that for a three times increase in the level of range anxiety, the number of required new EV charges increases by almost five times.

Comparing the locations of the allocated chargers under different scenarios, it can be observed that the spatial configuration of the study area has a significant impact on the results. For instance, it can be spotted that allocating a charger in an exact same location in the southwest corner of the area is part of the solution of all scenarios. In other words, the lack of existing chargers, in some areas, the allocation of a new charger is essential under all scenarios. In addition to these particular locations, two specific spatial patterns in the location of allocated chargers are visible. First, in case of the scenarios of low range anxiety, it is observed that the new chargers intend to fill the gaps between the existing chargers. For instance, in case of the SC#01, with exception to a few cases, the new chargers are allocated within the maximum distance possible from the existing chargers. Second, under the scenarios of high range anxiety, the new chargers are concentrated at the arterial streets of the area. In case SC#05, for instance, a spatial continuity of new chargers along the main streets of the area is visible (Figure 4).

A comparison between the overall cost of new EV chargers allocated under different scenarios shows that the overall cost ranges from less than 1 million euro, in case of SC#01, to almost 5 million euros, under SC#05. This indicates that if drivers use 90% of their battery before using a charging facility, the municipality needs to spend 920 euros per EV. The amount raises to 4520 euros if drivers charge the EVs when only 30% of the battery is empty. Range anxiety has also a significant impact on the efficiency of use of EV infrastructure, accounting for both new and existing chargers. The efficiency of use refers to the ratio of the total demand for charging (kWh) to the total capacity of charging infrastructure. The results show that in case that range anxiety is 90%, under SC#01, the efficiency is 50%. In other words, the chargers are on-hold or unused for only half of evenings. The efficiency could drop to half, that is 25%, if range anxiety is 30%, under SC#05 (Figure 5).

In the last part of the analysis, the financial gain in return for a reduction of range anxiety under different scenarios is measured. The result shows that under all scenarios of range anxiety if the interval between charging sessions of EVs increase for 1 day, the total cost of new infrastructure could be reduced to a minimum of 28%. In the most severe case, it is found that if the frequency of charging alters from every 2 days, case of range anxiety of 30%, to every 3 days, case of range anxiety of 45%, almost 1.9 million euros could be saved, accounting for almost 40% of the total costs (Figure 6).

SC # 01
Range anxiety = 90%
Frequency of charging = 6 days
Cost = 985,036 €
no of new chargers = 16

SC # 02
Range anxiety = 75%
Frequency of charging = 5 days
Cost = 1,368,908 €
no of new chargers = 23

SC # 03
Range anxiety = 60%
Frequency of charging = 4 days
Cost = 1,979,368 €
no of new chargers = 34

SC # 04
Range anxiety = 45%
Frequency of charging = 3 days
Cost = 2,943,056 €
no of new chargers = 52

SC # 05
Range anxiety = 30%
Frequency of charging = 2 days
Cost = 4,834,380 €
no of new chargers = 85

○ New charger (22 kWh with 5 plugins)
⬠ Existing charger (11 kWh with 2 plugins)

Figure 4. The results of optimization models employed for the 5 scenarios.

5. Discussion and policy implications

5.1. Information technology approach

Policies regarding EV infrastructure need to invest in information and communication technologies (ICT) which can effectively reduce drivers' level of range anxiety. In a seminal publication in the journal of Applied Psychology, through a 6 months study of a group of EV drivers, Franke et al. (2012) concluded that, to a large extent, range anxiety is affected by a subjective estimation of 'useable range', that is the amount of electricity needed to reach to the destination or the next charging station. The authors concluded that the stress-buffering and ambiguity-tolerance traits of the drivers have a significant influence on range anxiety. ICT infrastructure, such as smartphone applications, providing drivers with objective estimations of 'useable range', could be employed to alter such traits (Du and De Veciana 2013). The policies regarding EV infrastructure need to assign resources for the concurrent development of EV and ICT infrastructure. Connected to national servers providing data on real-time traffic, free-of-charge smartphone applications could provide drivers with accurate range estimations. Based on final destinations of the drivers, the remaining charge of their battery, and location of EV chargers, the application could offer an energy-efficient route specific to each driver. Using data on the previous use of EV chargers and expected traffic at different routes, the application could be used for advanced planning of journeys and realistic decision-making regarding battery charging (Yaqub and Cao 2012).
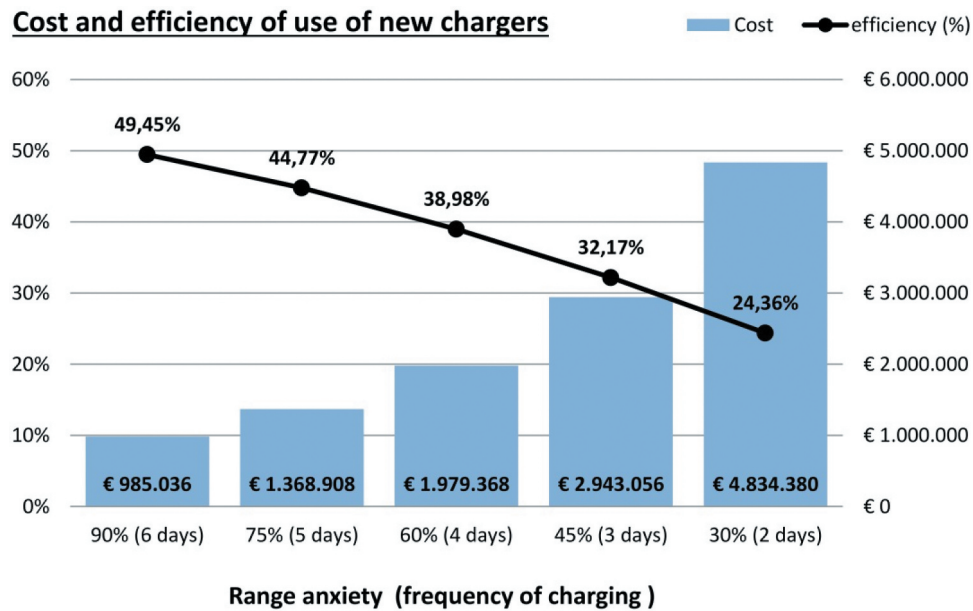
Cost and efficiency of use of new chargers

Legend: Cost · efficiency (%)

Figure 5. Total cost and efficiency of use of chargers under different scenarios of range anxiety.

Cost reduction by change of charging frequency
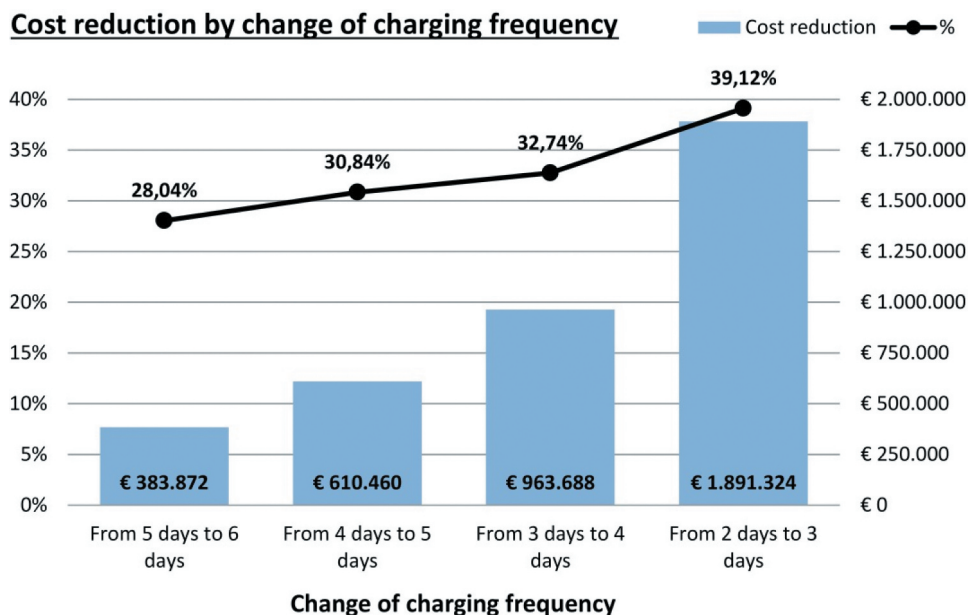
Legend: Cost reduction · %

Figure 6. The financial gain in return for decreasing the level of range anxiety.

5.2. Demand-response approach

EU legislations have laid the basis for adaptation of two types of demand-response policy measures aimed at the reduction of range anxiety: adjusting charging fees and regulating the access to charging stations. First, the policies could regulate charging fees to mitigate range anxiety, in accordance with the Article 15.4 of the Directive 2012/27/EU on energy efficiency which states that 'Member States shall ensure the removal of those incentives in transmission and distribution tariffs that are detrimental to the overall efficiency (including energy efficiency) of the generation, transmission, distribution, and supply of electricity [...]. Member States shall ensure [...] that tariffs allow suppliers to improve consumer participation in system efficiency, including demand response, depending on national circumstances' (Official Journal of European Union 2012. pp. L 315/22). Second, policies could adopt a framework by which access to public chargers is conditional to certain criteria, in accordance with the Article 26 of the European Parliament directive on the deployment of alternative

fuel infrastructure which grants the authority to determine when and how '[a] recharging or refuelling point [is] accessible to the public [...] through registration cards [...] which allow [...] private users physical access with an authorisation or a subscription' (Official Journal of European Union, 2014. pp. L 307/4).

To mitigate range anxiety, in line with the EU legislation, policies could adopt a version of two widely applied demand-response approaches: dynamic pricing rate and direct control – see the review by Albadi and El-Saadany (2008). A dynamic pricing approach refers to the arrangements by which the fee for one kWh of electricity differs in different cases. Under a dynamic pricing system, a per kWh fee rate could depend on the total amount of charging: the lower amount of charging, the higher the rate. In this respect, a range-anxious driver who occupies a charger for charging only 10% of his/her battery will be charged with a higher rate than a driver who charges 90% of the battery in one charging session. In a dynamic pricing system, EV drivers face two choices: either to lower their level of range anxiety or to compensate for the financial cost which it creates. A direct control approach refers to the arrangements by which access to EV infrastructure is allowed only if a certain criterion is met, e.g., an EV driver could not occupy a charging spot unless, say, at least 70% of her/his battery is empty. To adopt the latter approach, it is necessary to use EV charge cards which provide data on vehicles and record the charging behaviour of their drivers. The direct control approach could include measures like denying access, levying fines, and unplugging EVs (Bonges and Lusk 2016).

6. Further studies

In this study, it has been assumed that all the new chargers will be semi-fast chargers (Level II) with five plugins. Further studies on the allocation of EV chargers and range anxiety could allow for the allocation of different types of chargers, namely slow-chargers (Level I), semi-fast chargers (Level II), and fast-chargers (Level III), with a variant number of plugins (similar to the model adopted by Baouche et al. 2014). By locating a slow-charger with only one plugin, for instance, such models could adapt efficiently to the circumstances under which single highly range-anxious drivers are dispersed across a study area.

In this study, the impact of range anxiety on the number of necessary chargers is modelled. The relation could also be applied in the reverse direction: the number of chargers could affect the level of range anxiety. A variety of previous studies pointed out that when the number of charging station increases, range anxiety

tends to decline (see the review by Jing et al. 2016). Further studies could adopt models with feedforward mechanism assuming that after the allocation of every EV charger, range anxiety could alter.

Ultimately, further studies need to model the total electricity demand of buildings and EVs at each electricity substation. (This study only takes the latter into consideration.) In addition to the adaptation of electric mobility, the Dutch Climate Accord (Ministry of Economic Affairs and Climate Policy 2019) aims to phase out residential gas use for heating and cooking before 2050. The transition from gas to electricity in residential buildings will reshape the patterns of electricity consumption (Mashhoodi et al.,2018) which alongside urban microclimate (Mashhoodi, 2020) and its future changes can increase the load on electricity substations. Future studies on the optimal allocation of EVs and the impact on range anxiety need to incorporate the overall upcoming demand for electricity.

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