The Recharging Infrastructure Needs for Long Distance Travel by Electric Vehicles: A Comparison of Battery-Switching and Quick-Charging Stations

Linda Christensen, Sigal Kaplan, Thomas C. Jensen, Stefan Røpke, and Allan Olsen

Abstract On-road electric vehicle recharging infrastructure is essential in the transformation of electric vehicles into a practical transportation option. This study focuses upon assessing the need for recharging infrastructure for long distance travel for a large market share of electric vehicles, finding the optimal infrastructure deployment, and understanding the economic, social and environmental costs and benefits associated with the optimal infrastructure deployment. The analysis considers quick-charging and battery-switching as plausible recharging technologies. Results show: (i) the promotion of electric vehicles is beneficial when considering economic costs and benefits for operators and users, tax redistribution, and environmental externalities, even with a relatively modest market share; (ii) the number of required recharging stations for satisfaction of the travel demand is at the magnitude of 1–2% of the current gasoline infrastructure, under the assumption of wide availability of off-road recharging at home and the workplace; (iii) the optimal deployment of the recharging stations is along the main national highways outside of urban conurbations, under the assumption of wide availability of home recharging; (iv) the battery-switching technology is far more attractive to the consumer than the quick-charging technology for long-distance travel requiring more than one recharging visit.

Keywords Electric vehicles • Recharging stations • Location optimization • Socio-economic analysis • Battery-switching • Quick-charging • Spatial-optimization • EVs

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L. Christensen • T.C. Jensen • S. Røpke • A. Olsen
Department of Management Engineering, Technical University of Denmark, Bygningstorvet 116, B 2800, Kongens Lyngby, Denmark
e-mail: lich@dtu.dk; tcje@dtu.dk; ropke@dtu.dk

S. Kaplan (✉)
The Geography Department, The Hebrew University, Mt. Scopus, Jerusalem 9190501, Israel
e-mail: Sigal.kaplan@mail.huji.ac.il

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Introduction

The mass utilization of electric vehicles (EVs) was proposed at the end of the 1970s as a remedy for an automobile market under the constraints of an oil shortage, high oil prices, and depletion of environmental resources (Blair 1978; Charlesworth and Baker 1978). Research efforts during more than three decades have focused on technological improvements, market penetration, and impact assessment of EVs (Blair 1978; Carmody and Haraden (1982); De Luchi et al. 1989; Giese et al. 1983; Hamilton 1980; Kurani et al. 1994). However, the market penetration of EVs has been negligible so far because of high unit costs, limited driving range, and lack of recharging infrastructure (Chéron and Zins 1997; Dagsvik et al. 2002; Pearre et al. 2011). Nevertheless, recent years have witnessed growing expectations for a rapid EV growth in the future, following battery technology innovations and governmental commitment to EV promotion through legislation, investments, and taxation policies (Andersen et al. 2009; Brady and O'Mahony 2011; Brown et al. 2010; Dagsvik et al. 2002; Hidrue et al. 2011).

Adequate EV recharging infrastructure has a key role in transforming EVs into a viable transportation option for large-scale adoption (Andersen et al. 2009; Dagsvik et al. 2002; Hidrue et al. 2011; Wang and Lin 2009; Christensen 2011). Accordingly, a significant body of research has been dedicated to developing recharging technologies (Calasanzio et al. 1993; Fernández and Trinidad 1997; Yang and Liaw 2001) and promoting recharging standardization (Brown et al. 2010). In parallel, research has been devoted to impact assessment of EV recharging on the electric power system. Themes of interest are the minimization of the burden induced by vehicle recharging on the power grid (Hartmann and Özdemir 2011; Mullan et al. 2011; Perujo and Ciuffo 2010); the dual role of EVs as both consumption and storage devices (Andersen et al. 2009; Kristoffersen et al. 2011); and the development of intelligent grid management systems that allow power load optimization for example by allowing flexible recharging rates according to the power consumption rate (Ahn et al. 2011; Amoroso and Cappuccino 2011; Van den Bossche 2010).

The optimal deployment of EV recharging stations on the basis of consumer behavior is scarcely explored, although a handful of studies sheds light on the infrastructural needs and optimal deployment of refueling stations for hydrogen and natural gas (Frick et al. 2007; Kuby and Lim 2005; Kuby et al. 2009; Nicholas et al. 2004). Differences exist in terms of objective functions, as Nicholas et al. (2004) proposed minimizing the travel time to the refueling stations, Kuby and Lim (2005) and Kuby et al. (2009) focused on maximizing the refueled traffic volumes without changes in the selected routes, and Frick et al. (2007) considered a multiple-objective function including the minimization of travel distance to population conurbations, the locations of pipelines, and commercial opportunities. Recently, Kim and Kuby (2012) proposed a model that allows vehicles to deviate from shortest paths in order to refuel. Differences exist also in terms of scale, as Kuby and Lim (2005) and Kim and Kuby (2012) considered a synthetic network, Nicholas et al. (2004) referred to metropolitan regions, while Frick et al. (2007) considered a national model for Switzerland. Kuby et al. (2009) explored both a metropolitan scale model for Orlando and a state scale model for Florida.

The unique features of EVs impede the direct application of the aforementioned methodologies to the optimal location of EV recharging stations. First, EV recharging can be done anywhere (i.e., at home or at activity location), provided adequate connection to the electricity grid, and hence the assumption that people prefer to recharge in proximity to their origin or destination is not necessarily substantiated in the case of EV recharging behavior. Second, the location of EV recharging infrastructure is highly flexible since it is independent of current or planned networks for the deployment of natural gas or hydrogen pipelines.

Only a few recent studies examined the optimal deployment of EV recharging infrastructure revealing that this line of research is still at its nascent stage. Wang and Lin (2009) proposed a model that selects a set of stations to locate, minimizing total cost, such that all vehicle paths given as input to the model are feasible. The model is used for locating EV quick-charging stations for intercity travel along a coastal road in Taiwan. Wang and Wang (2010) extended the previous model by including a dual-objective function of minimum location cost and maximum population coverage. Li et al. (2010) suggested using demand-responsive portable recharging units and analyzed a synthetic network assuming 100 EVs.

The current study joins the line of location optimization research for EV recharging stations by assessing the need for on-road EV recharging stations based upon travel patterns. The purpose of this analysis is to provide an efficient spatial distribution of EV recharging stations at the national level, with a focus upon understanding its benefits and costs while considering economic, social and environmental goals. The importance of this issue is threefold. First, although evidence suggests that consumers would prefer overnight recharging at home over on-road recharging stations (Skippon and Garwood 2011), the deployment of publicly accessible recharging infrastructure remains important as a pre-condition for large-scale EV market penetration in urban and rural areas (Andersen et al. 2009; Dagsvik et al. 2002; Hidrue et al. 2011; Wang and Lin 2009). Second, understanding the costs and benefits of quick-charging versus battery-switching is of interest since these technologies are currently underway in several world regions including Australia, Asia, Europe, and the United States. Finally, EV recharging infrastructure requires significant private and public investments for infrastructure development (Andersen et al. 2009; Li and Ouyang 2011). Consequently, efficient infrastructure deployment is essential, in particular in the initial stages of EV market penetration.

The contribution of the current study to the locational optimization literature regarding EV recharging infrastructure is fourfold. First, while existing studies on EV recharging stations have focused on small-scale local networks, the current study analyzes a nationwide case including thousands of potential EV chanrging station locations. Second, while previous studies regarding the location of EV recharging stations have represented the consumer perspective, the current study proposes a comprehensive socio-economic analysis including social and environmental considerations. Third, while previous studies on the location of EV stations have ignored possible travel pattern changes due to recharging, the current study -in line with the recent study of Kim and Kuby (2012) on hydrogen refueling stations - accounts for detours from the originally intended route, due to the need to reach the EV recharging stations. Finally, the current study considers home-based EV recharging opportunities.

The remainder of the paper is organized as follows. Section "Case study: Denmark" describes the background of the case study. Section "Methodology" presents the methodology applied in the current study. The results of the empirical analysis are introduced in the "Results" section. Finally, section "Discussion and conclusions" presents a discussion of these results; conclusion are also drawn and further research is proposed in this last section.

Case Study: Denmark

Background

Denmark, renowned as a world leader in clean energy production and high energy efficiency, is seeking to decrease the fossil fuel dependency in the transport sector. Consequently, in addition to its high taxation on the purchase of private vehicles, the Danish government allocated a large budget for research regarding EVs between the years 2008 and 2011 and currently grants a tax exemption for the purchase of new EVs until 2015. Furthermore, as part of the energy strategy for 2050, the Danish government intends to establish a specific fund for kick-starting EV recharging infrastructure, encouraging EV standardization, promoting research and development efforts for renewable energy in the transport sector, and acting to tighten European Union standards on vehicle energy efficiency and CO_2 emissions. As yet another part of this energy strategy, the Danish government has an ambitious goal of 18% reduction in fossil fuel consumption in the energy and transport by 2020, and an even more ambitious goal of 100% renewable energy in 2050.

Although the current EV market share is negligible (approximately 500 registered EVs nationwide in 2011), several studies predicted its potential in Denmark on the basis of different market conditions. Eskebæk and Holst (2009) predicted an EV market share of 13% by 2020 on the basis of semi-structured interviews with key consultants in the EV and energy sectors, media articles and car industry statistics. Better Place, an international company developing EV battery-switching and charging devices, was more optimistic, expecting EVs to achieve 20% of Danish market share by 2020 (Rosted et al. 2009). Similar expectations were embraced by Kristoffersen et al. (2011). Based upon a stated preference survey among 1593 new car-buyers and the assumptions of a 150-kilometer EV range and a vehicle purchase price of about EUR 25000 Euros, Mabit and Fosgerau (2011) predict a much higher potential EV market share. Thus, the market share of EVs is expected to be significant, necessitating efficient infrastructure deployment.

Road Network and Candidate Locations

The current road network in Denmark totals 73,197 km of paved roads, including 1111 km of motorways. Along the road infrastructure there are about 2200 gasoline stations, of which 87% are considered as possible candidates for EV recharging stations. The candidate facility locations are distributed across Denmark's regions with about 13% in the capital region of Copenhagen. Regarding the distribution of the candidate locations according to the road hierarchy, 27% are located near national motorways, 43% near arterial roads, 30% near regional roads, and only 0.3% near local roads.

Technology Scenarios

The year 2020 serves as the target year for scenario development. EV off-road recharging infrastructure is assumed to be widely available to the general public in Denmark by 2020 in agreement with the goals of the Danish government for the reduction of fossil fuel dependency and the development of EV infrastructure. Specifically, two types of off-road recharging facilities are currently considered: normal plugs and recharging poles. Normal plugs facilitate overnight recharging at home with the connection to the existing electricity grid. The price of the plug is assumed to be an integral part of the EV purchase transaction and therefore its price is internalized in the EV purchase price. The recharging speed of poles depends on the number of phases and the electric current. For example, a single-phase 16 ampere recharging pole can charge a medium-size EV in 7 h, while a three-phase electric power recharging pole reduces the time to less than 3 h. As a result of off-road charging infrastructure availability at home, at workplaces and shopping facilities, the main charging demand for on-road recharging stations will comprise long-distance travelers with a daily kilometrage of over 100 km.

The representation of the road network for the target year was conducted by using the road infrastructure development for 2020 embedded in the Danish National Transport Model. The network comprises 31,533 links and contains information about the road hierarchy, directionality and number of lanes, length, and speed limit. In order to simulate realistic traffic flow conditions, average daily traffic volumes were assigned to the network and congested travel speed was calculated. Average daily traffic volumes were preferred over morning peak hour volumes since long-distance travel is distributed across daily periods.

The current study assumes a driving range of 150 km and a practical driving range of 120 km for a medium-size EV with maximum speed of 110 km/h. Currently, the new generation of EVs with Li-Ion batteries have a driving range of 120–180 km before recharging is necessary. However, these driving ranges are only obtained if cars are driving at a speed of 80 km/h, and are significantly shorter when the speed exceeds 110 km/h (Christensen 2011). Notably, the choice of vehicle with a specific driving range by Danish drivers derives not only from technological limitations, but also from driving needs. Since over 90% of the Danish travelers have a daily kilometrage of up to 100 km, it is reasonable to assume that the main market demand would be for low-cost medium range EVs.

Two technology scenarios are evaluated on the basis of existing recharging technology: differentiating between quick-charging and battery-switching. Quick-charging stations have sufficiently high voltage to recharge 80% of the battery in approximately 20 min. Battery-switching stations replace the EV battery pack with a fully charged battery in approximately 5 min. Both scenarios assume service times according to information currently available from recharging suppliers, and no waiting times according to the assumption of sufficient capacity to provide immediate recharging services. Other than for their features, the two technologies differ in terms of their construction costs, which are expected to be about EUR 34,000 (DKK 250,000) for quick-charging stations and about EUR 400,000 (DKK 3000,000) for battery-switching stations.

In terms of externalities, the current study accounts for emissions from the usage life-cycle phase, namely emissions resulting from electricity production and vehicle tailpipe emissions. The current study assumes zero CO_2 emissions from EVs, while CO_2 emissions from fossil-fueled vehicles are assumed to decrease with the improvement of European Union Standards. The argument for zero emission from EVs is reasonable due to the Danish transition to wind and bio-mass energy, and assuming that power production is covered by the European carbon trading system Danish Government (2011). The costs of other tailpipe pollutant emissions from EVs are assumed to be roughly 40% of the tailpipe emission costs of other vehicles. The costs of EV noise emissions also comprise roughly 40% of the noise emissions from fossil-fueled vehicles. In the absence of data regarding the impact of EVs on road safety, the current study assumes the same accident costs per kilometer for EVs and fossil-fueled vehicles.

Methodology

The research methodology included four steps: (i) evaluating the need for EV recharging stations on the basis of travel and activity patterns; (ii) analyzing the induced EV market share on the basis of the optimal infrastructure deployment; (iii) examining the optimal deployment of on-road EV recharging stations to satisfy the travel demand under land-use constraints on possible recharging sites; (iv) analyzing the costs and benefits associated with the optimal deployment of infrastructure.

Identification of Travel Patterns That Necessitate Recharging

Evaluating the need for recharging stations was conducted by means of agent-based recharging heuristics on the basis of the Danish National Travel Survey (NTS), while considering expected trends regarding EV driving range and a prominent scenario regarding the deployment of EV recharging infrastructure in Denmark (see Christensen 2011).

The agent-based recharging heuristics account for daily driving distance, available time windows for recharging on the basis of the drivers' activity patterns, urban versus interurban driving cycle, season, availability and type of recharging infrastructure at activity locations, and EV capabilities, such as range and speed. Car manufacturers' data provide the input to the heuristics in terms of size, driving range, maximum speed, battery and engine capacity, and estimated market prices of EVs.

The data regarding the travel and activity patterns are extracted from the NTS dataset for the period 2006–2010 from a representative sample of 47,848 car-using respondents. The survey data consist of respondents' 24-h travel diaries detailing individual trips and activities, as well as socio-economic characteristics. Although the NTS contains data related to fossil-fueled cars, it is currently the most suitable source in Denmark for evaluating the needs of EVs derived from travel and activity patterns. The NTS contains detailed information regarding the travel patterns of one adult in each household, rather than of all household members.

The current study overcomes this limitation for households with more than one licensed driver by employing hot-deck imputation (as detailed in Andridge and Little 2010) that generates matching household members on the basis of relevant criteria for car use, such as region, urban area type, travel weekday, family type, age and gender. Following the imputation procedure, car travel patterns are generated on the basis of the number of cars and complementary car use across household members and daily periods. The sample representativeness is maintained by adjusting the weights of respondents who have a dual role as both individuals and matching household members.

Assessment of EV Market Share

The market share analysis is based on 2976 observations obtained via a stated preference (SP) survey of 372 respondents (Jensen et al. 2012). The recharging technology for on-road stations in the survey was assumed to be a generic technology with 5–10 min recharging time (Jensen et al. 2012).

A logit model was estimated for the purchase propensity of EVs as a function of vehicle characteristics and infrastructure deployment as follows (Train 2002):

Table 1 Logit model for EV market shares. Elasticities are calculated with EVs representing 1% of the car market

Variable	Unit	Range	Elasticity
Purchase price	1000 DKK	19–998[a]	−2.02
Fuel costs (EV)	DKK/km	0.14–0.52	−0.84
Fuel cost (conventional)	DKK/km	0.26–1.39	0.61
Driving range (EV)	Km	112–208	1.22
Driving range (conventional)	Km	420–910	−0.36[b]
Carbon emission (EV)	g/km	34–127	−0.95
Carbon emission (conventional)	g/km	70–234	0.74
Top speed (EV)	km/h	94–173	1.73
Top speed (conventional)	km/h	111–230	−0.98
Battery lifetime (EV)	1000 km	100–250	0.69
Number of battery stations	Amount	0–30	0.31
Charging at work place	Dummy	0/1	0.25
Charging in city centers and at larger train stations	Dummy	0/1	0.33
Charging in city centers	Dummy	0/1	0.28
Charging at larger train stations	Dummy	0/1	0.21

Source: Jensen et al. (2012)

[a]The lower bound for the purchase price reflects that in some cases the respondents chose a used reference car

[b]The parameter is non-significant at the 5% confidence level (i.e. the elasticity could be 0)

$$P_{ni} = \frac{e^{V_{ni}}}{\sum_{j=1}^{J} e^{V_{nj}}} = \frac{e^{\beta' x_{ni}}}{\sum_{j=1}^{J} e^{\beta' x_{nj}}} \tag{1}$$

where P_{ni} is the probability of individual n to choose alternative i given J alternatives ($j = 1, \ldots J$), x_{ni} is the vector of alternative attributes for alternative i and individual n, and β is the vector of parameters to be estimated.

Results presented in Table 1 illustrate that consumers evaluate EVs versus fossil-fueled vehicles by considering purchase price and operating costs, vehicle capabilities, and environmental aspects. Availability of on-road recharging stations, recharging facilities at the workplace, and possibility to recharge close to home or at public parking lots only play a minor role in the acceptability of EVs.

Since the model is constructed in a hypothetical setting, it is necessary to calibrate the model to reproduce recently observed EV sales by adjusting the constant term for EVs (ASC_{EV}). This is a non-trivial task since EV sales are presently low and possibly reflect the initial state of a market penetration curve rather than an equilibrium state. In order to account for the uncertainty about the initial state of the demand curve, the model is calibrated for two alternative base-year scenarios. In the first scenario, the model is calibrated for the actual number of sold cars retrieved by using the recent sales figures from the Danish Car Importers Association. The figures show that the annual sales will probably reach 500 EVs in

2012. Nevertheless, the EVs that are currently on the market in Denmark only cover around 50% of the market because of the unavailability of the electric versions of medium sized cars, multi-purpose vehicle versions of small family cars and sport utility vehicles. Therefore, in the second scenario the model is calibrated while considering the recent market penetration of an electric version of a typical five door family cars which represents half of the market share in Denmark. According to this scenario, the EV car sales in 2013 are expected to rise to 900 cars.

Edison Model for Optimal Location of EV Recharging Stations

This study optimally locates quick-charging stations by applying an improved version of the methodology firstly developed as part of the Edison project (Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks, see Olsen and Nørrelund 2012). The input for the optimization procedure includes: (i) the road network and link flow speeds according to the traffic conditions; (ii) daily tours as trip sequences between origins and destinations; (iii) assumed off-road recharging infrastructure; (iv) the characteristics of the trips that necessitate recharging according to the travel pattern analysis (i.e., origin, destination and trip schedule); (v) the desired number of EV recharging stations; and (vi) candidate locations for EV recharging stations. The output of the optimization procedure consists of: (i) the optimal spatial deployment of EV recharging stations according to the defined objective function; (ii) the number of recharging incidents per station and per daily journey; and (iii) the route detour per trip due to recharging in terms of time and distance traveled. Hence, the output provides valuable insights regarding the efficiency of the infrastructure deployment from both the private investors' and the consumers' perspectives.

The model structure consists of the three stages illustrated in Fig. 1.

At the first stage, the potential recharging points per tour are identified on the basis of the chosen travel routes. The need to recharge is identified as a function of travel distance, speed and driver's assumed risk aversion. The chosen travel route is selected according to the shortest path algorithm, while allowing users to define the objective function for minimization on the basis of a linear combination of travel distance and congested travel times. The potential recharging demand points are estimated by a simulation procedure considering: a constant battery discharge rate; a homogenous risk aversion buffer of 20 km remaining driving range demarcating the decision point at which the search for a recharging location begins; a driving range of 120 km; and a recharging rate of 80% for quick-charging and 100% for battery-switching. Notably, the model assumes that recharging is possible at intermediate stops where other activities are performed, provided that the activities are of sufficient duration.

Figure 2 illustratesthis concept, as a single tour from A to B is presented at the top of the figure. The tour represents an actual tour extracted from the Danish National Travel Survey. At the top, the intersections and cumulative distance (in kilometers)

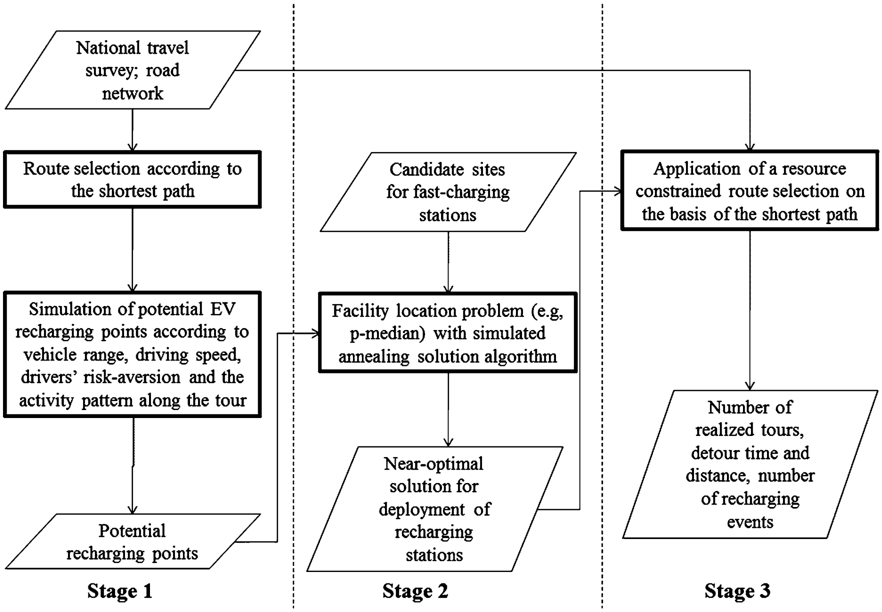

Fig. 1 Edison model structure for the optimal location of recharging stations

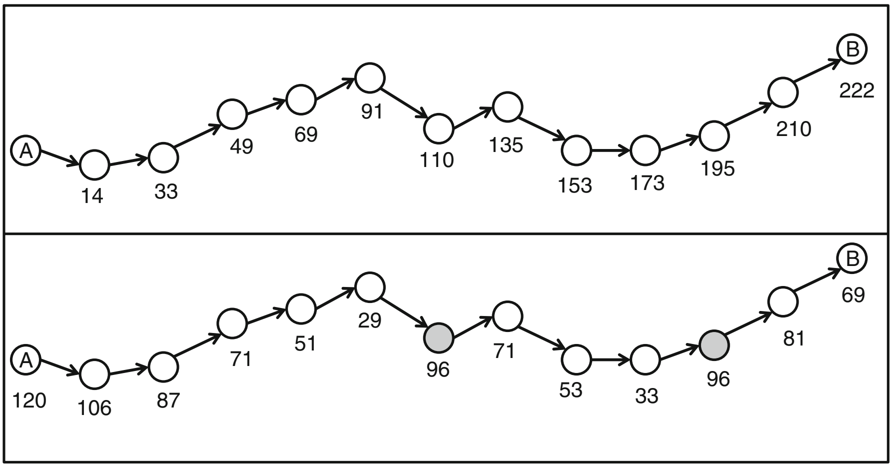

Fig. 2 Calculating potential recharging points. *Top*: A tour from node A to node B extracted from the Danish National Travel Survey; cumulative distance from node A is depicted. *Bottom*: The same tour is illustrated with remaining driving range and potential recharging points

along the tour are depicted. At the bottom, the potential recharging points that result from this tour are presented (assuming that the quick-charging technology is used) with the remaining driving range (in kilometers) at each node according to the discharge rate of the battery. While traveling from the sixth to the seventh node heading from A to B, the vehicle exceeds the 20 km threshold and the seventh node is consequently selected as a potential recharging point. The range of the vehicle is reset to 96 km (80% of the battery range of 120 km), assuming that the vehicle is quick-charged at this point. Between the tenth and eleventh node the remaining range drops below 20 km again, and node 11 is selected as the second potential recharging point. The potential recharging points for all tours are used as input (EV demand points) to the facility location model.

At the second stage, the model seeks the optimal deployment of recharging stations on the basis of the distribution of the potential recharging points and the candidate sites for EV recharging stations. The current study employs a *p*-median facility location problem (as in Tansel et al. 1983) to find the near-optimal deployment of *p* recharging stations by minimizing the total driving distance/travel time from EV demand points to the recharging stations. Because the number of facilities is too large to be solved to proven optimality, a simulated annealing meta-heuristic is used to find a near-optimal solution of the *p*-median facility location problem (for details, see Olsen and Nørrelund 2012).

At the third stage, given the optimal deployment of the recharging stations, travel routes between origins and destinations along the tour as a trip sequence are re-selected on the basis of a resource constrained shortest path algorithm (Irnich and Desaulniers 2005). Hence, trips that require en-route recharging are re-routed in order to perform the recharging task at recharging stations, resulting in detours. Trips that cannot be served by the recharging infrastructure due to the length of the detour are aborted, thus simulating the share of trips that would not be performed due to the lack of infrastructure. The number of recharging incidents per tour and per station is also calculated at the third stage. Further details regarding the algorithm employed in stage three can be found in Røpke et al. (2012).

Socio-economic Evaluation

The socio-economic analysis accommodates the calculation of user benefits and detour costs, investments and operational costs, externalities (e.g., noise emissions, greenhouse gases and other pollutant emissions), and tax distortion.

The current study employs a utilitarian approach for estimating the road user benefits. In particular, the consumer surplus due to the change in the number of on-road recharging stations is calculated on the basis of the logit model for the purchase of EVs as follows (Train 2002):

$$\Delta E\left(CS_n\right) = \frac{1}{\alpha_n}\left[\ln\left(\sum_{j=1}^{J^1} e^{V_{nj}^1}\right) - \ln\left(\sum_{j=1}^{J^0} e^{V_{nj}^0}\right)\right] \quad (2)$$

where α_n is the estimated car price parameter, and the indices zero and one refer, respectively, to the base case and the change in the attribute. This expression accounts for the perceived costs and benefits during the hypothetical vehicle purchase in the SP experiment, and can be interpreted as the percentage change in the consumer's willingness to pay as a result of a change in one EV attribute. The total user benefits are obtained by multiplying the consumer surplus in the total new car sales (conventional cars and EV) after the change in the attributes.

The detour costs are calculated independently and added as a cost, with the argument that the daily detour costs could not be foreseen by the respondents to the SP survey. The survey only provided information about an ideal recharging time of 5–10 min per visit; it did not provide any information regarding the daily number of recharging stops required or the need to make a detour in order to reach recharging stations while on long distance trips. The detour costs are calculated on the basis of the value of time DKK 80 per hour used in transport feasibility studies in Denmark. A penalty for infeasible trips resulting from lack of recharging infrastructure along the route is assumed to amount to three extra traveling hours. The detour externalities are included as costs.

The costs associated with the recharging infrastructure are the operation and maintenance costs of the recharging stations and charging poles in the cities. The total building cost of the battery-switching stations is approximately DKK 3 million; operating cost is assumed to be 10% of annual investment costs.

The externalities cover climate change, air pollution and noise and are based upon the assumptions in the Danish Transport Economic Unit Prices (Danish Ministry of Transport 2010). CO_2 emissions from EVs are set to zero within the European Emission Trading System. The cap on the total emissions from heavy industry and power production means that extra emissions due to a larger EV fleet are offset by reductions elsewhere in Europe. It is assumed that, apart from recharging detours, the total amount of traffic remains the same - i.e. the annual kilometrage of both EVs and conventional cars remains 18,000 kilometers.

The tax distortion is set to 20% of the net revenue loss in accordance with the guidelines from the Danish Ministry of Finance (1999).

All of the costs and benefits over the years 2012–2030 are calculated as the net present value in 2012 with a 5% interest rate.

Results

Demand for EVs

The model presented in Table 1 is used to predict the market share of new EV sales. The prediction is based on the assumption that the market price of EVs excluding the battery will decrease to the level of conventional cars in 2020, and that the battery price would decrease by approximately 40% (Danish Energy Authority 2011). In addition, the tax exemption for EVs will be in place until 2015, but the registration tax for EVs would still be lower than the registration tax of conventional cars due to their higher energy efficiency.

According to the demand model predictions, considering the alternative base-year sales scenarios of 500 EVs (low-demand) and 900 EVs (high-demand), respectively, the EV fleet in 2020 will increase to 8600 for the first scenario and 15,200 vehicles for the second scenario (comprising a maximum of 0.6% of the total vehicle fleet) in the absence of on-road recharging infrastructure. The effect of the additional recharging stations can only be calculated for the battery-switching technology because the SP survey considered only an ideal recharging time of 5–10 min. The additional demand for EVs in 2020 that is generated by the deployment of on-road battery-switching infrastructure is predicted to be 3000–5000 vehicles with 15 battery-switching stations; 7000–12,000 with 30 stations; and 14,000–26,000 with 50 stations, under the conditions of the low-demand and high-demand scenarios, respectively.

Travel Patterns and Infrastructure Deployment

Table 2 presents the average number of recharging visits per daily tour, the average detour time per recharging visit, and the average detour time and distance per daily tour. The distribution of the number of recharging visits per daily tour is a decaying exponential function with most travelers recharging only once or twice daily. While the detour distance is significantly reduced with the increase in the number of recharging stations, the detour time does not significantly decrease, indicating that the detour time is mostly a result of the recharging time rather than the detour travel time.

A small share of the travelers cannot reach a recharging station if only 15 recharging stations are deployed. This share is negligible when the number of facilities is increased to 50 quick-charging stations or 30 battery-switching stations.

Notably, the recharging time per daily tour for the quick-charging technology is more than triple the recharging time of the battery-switching technology. Under these conditions, it can be assumed that the quick-charging technology would not be an inducement to purchase a new EV for the purpose of long-distance travel.

Figure 3 shows the optimal locations of EV recharging stations and the number of recharging visits at each station. For the quick-charging technology, the number of visits is based upon a total EV fleet of 15,200 vehicles in 2020. Notably, while it is not assumed that this technology would be an encouraging factor in the purchase of EVs for long-distance travel, it is assumed that consumers who already bought EVs would use them also for the purpose of long-distance travel. For the battery-switching technology, Fig. 3 depicts the high-demand scenario. As expected, most of the stations - as well as the busiest stations - are located along the main national highways outside urban conurbations.

For two reasons the location of recharging stations is different for the two technologies. The first reason is that the range of an EV after a quick charge is lower

Table 2 Results from the recharging infrastructure deployment model for 15, 30 and 50 quick-charging stations and battery-switching stations

	Quick-charging stations			Battery-switching stations		
	15	30	50	15	30	50
Average number of recharging visits per daily tour (number of visits)	2.35	2.10	2.06	1.91	1.84	1.81
Average detour and recharging time per daily tour (minutes)	67.03	52.63	48.94	21.18	18.64	16.52
Average detour travel time per daily tour (minutes)	19.96	10.55	7.69	11.64	9.46	7.48
Average detour distance per day (kilometers)	21.45	8.66	5.52	11.09	8.62	5.76
Average detour and recharging time per recharging visit (minutes)	28.48	25.02	23.73	11.10	10.15	9.14
Average detour distance per recharging visit (kilometers)	9.11	4.12	2.67	5.81	4.69	3.18
Share of cars that need to charge which are unable to charge (percent)	5.7	3.9	1.0	3.5	0.8	0.3

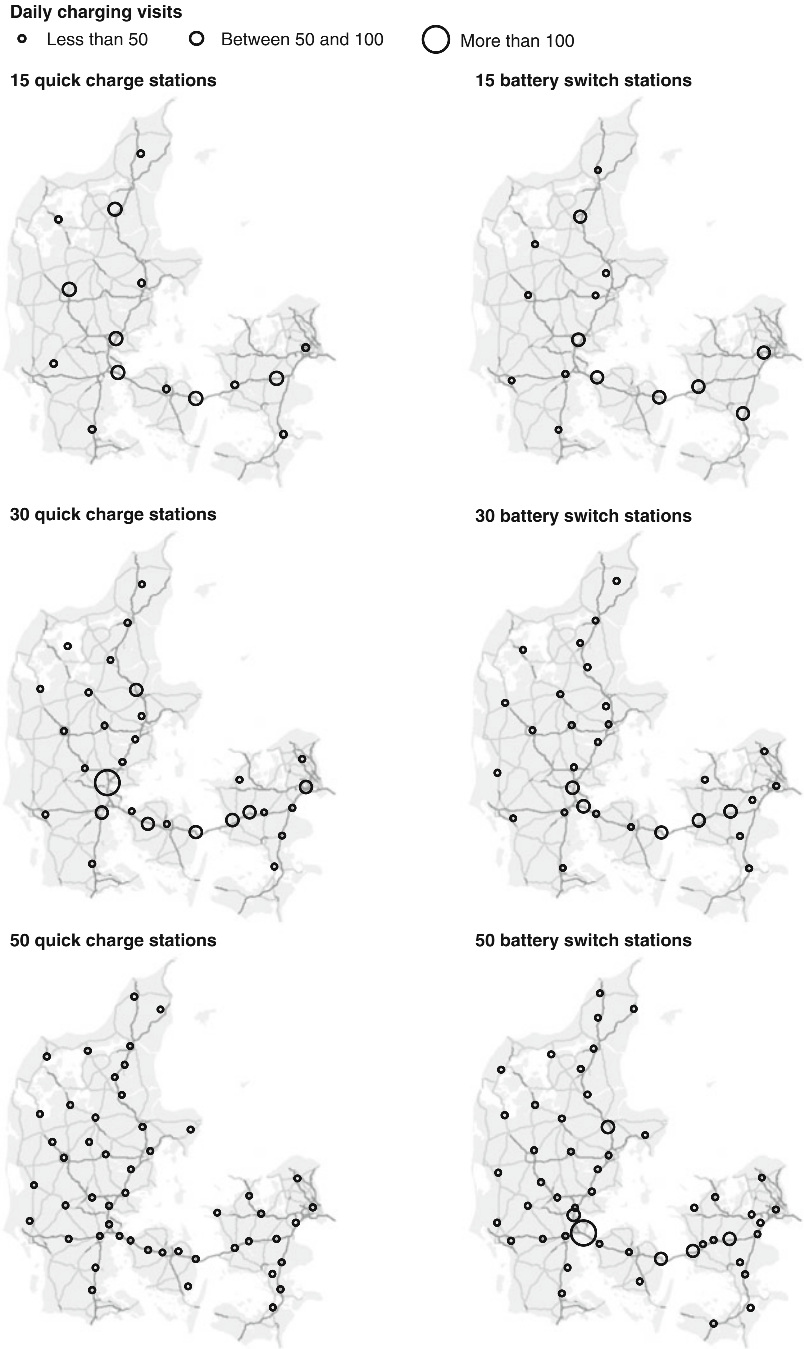

Fig. 3 The locations of 15, 30 and 50 quick-charging and battery-switching-stations

Table 3 Results of the socio-economic analysis under the high-demand scenario (900 EV sales in 2013)

Monetary benefits (Millions DKK[a])	15 stations	30 stations	50 stations
Consumer surplus	1366	3215	6713
Tax distortion	−328	−767	−1579
Investment and operation	−114	−228	−379
Externalities (excluding CO_2)	134	312	638
Detour costs	−58	−103	−173
Net benefits (million DKK)	1000	2429	5220
CO_2 reduction (kiloton)	159	372	770

[a] 1 EUR = 7.5 DKK

than the range of an EV after a battery change. The second reason is that the set of locations is the output of a stochastic search procedure, which is a near-optimal solution.

Socio-economic Analysis

According to Table 3, in the case of the high-demand base-year scenario, the benefit of deploying 15 battery-switching stations and equipping all EVs with a switchable battery is assessed to be DKK 1.0 billion. In the case of the low-demand scenario, the benefit is halved.

The results are highly dominated by a road user benefit of more than DKK 1.366 billion calculated as the consumer surplus. Notably, the benefit of the reduced externalities is only 10% of the consumer surplus. The most important cost is a tax distortion, which consists of government revenue loss on purchase tax, energy taxes, etc. Investment and operation of the recharging infrastructure, and the detour costs, both have a lesser effect.

The socio-economic benefit gained by the addition of one recharging station increases with the number of stations, from DKK 67 million for 15 stations to DKK 162 million for 30 stations, and DKK 261 million for 50 stations. This increase is due to the perceived consumer benefit due to the additional recharging opportunities, as well as to the increase in the EV fleet as a result of the increase in the number of stations.

Discussion and Conclusions

The results show that wide-scale market penetration of EVs is correlated with infrastructure deployment. Deployment. This finding is in accordance with previous studies (Christensen et al. 2010; Hidrue et al. 2011; Stathopoulos and Marcucci

2012). Furthermore, the results show the importance of efficiency in deployment of EV recharging stations, as only 15 battery-switching stations or 30 quick-charging stations (1–2% of the current infrastructure) are sufficient for satisfying the recharging needs of 96% of the EV stock. Notably, the results obtained are under the assumption that by 2020 in Denmark, EV off-road recharging infrastructure will be widely available at home, at workplaces and at shopping centers for use by the general public. Therefore, the main demand for on-road recharging stations will be comprised of long-distance travelers with a daily kilometrage of over 100 km.

The results indicate that, under the assumption of optimal infrastructure deployment, the main reason for time and production losses as a result of recharging detours is related to the recharging time rather than to the detour travel time or detour distance. The results show that for long-distance travel the average detour time for a long-distance daily tour including recharging with quick-charging technology is about 50–60 min. Considering that long recharging time is among the three main concerns of consumers along with range anxiety and purchase price (Hidrue et al. 2011), spending 50–60 min per day at quick-charging stations may be a severe barrier to EV market penetration. This barrier is largely alleviated if battery-switching is considered since the recharging time reduces to only 15–20 min for a daily long-distance tour, which is nearly equivalent to re-filling a gasoline tank several times. Moreover, battery-switching would be associated with lower driving range anxiety due to the higher recharging capacity allowing fewer daily recharging incidents. Thus, according to the results of the current study, battery-switching seems a better solution in terms of alleviating the barriers for wide-scale EV adoption.

The current study does not explicitly incorporate capacity constraints. However, the results indicate that some recharging stations will serve over 50 cars daily. Therefore, stations should be designed to accommodate the daily distribution of recharging visits with adequate capacity in order to avoid aditional waiting time.

The analysis shows that a reduction of 160–770 Kilotons in CO_2 is feasible for the target year of 2020, assuming a relatively modest share of EVs comprising 0.7–1.5% of the total vehicle stock. This reduction is feasible without major policy changes apart from full availability of off-road recharging options at home and at activity locations, and the efficient deployment of EV recharging infrastructure. Interestingly, this result is in agreement with the assessment of the Rotterdam Climate Initiative (RCI) that such a reduction is possible by introducing green vehicles and fuels (Geerlings 2012).

The socio-economic analysis shows the positive net benefit of providing battery-switching station infrastructure. Results show that of the benefits of EVs, a large part is related to the willingness to pay, which is estimated on the basis of an SP survey. Notably, SP survey are associated with a high degree of uncertainty; in particular, SP surveys are susceptible to compatibility bias and strategic response bias. The former bias occurs when respondents are not responsible for the consequences of their selection, while the latter bias occurs when respondents anticipate that their responses would influence product design. Compatibility bias could result in overestimation of the consumer willingness to pay, while Strategic response bias could result is overestimation of the required EV features, for example speed and range. Nevertheless, SP surveys are the best tools for investigating technologies with little or no market penetration. Bearing these limitations in mind, the current study shows that even with a relatively modest market share, promoting the EV could be beneficial.

The current study is the first analysis of the deployment of EV recharging stations from a comprehensive socio-economic perspective. However, the study is not without limitations, and as such it helps to uncover several interesting issues for further research regarding optimal location of EV recharging infrastructure. First, the current study is based upon relatively conservative assumptions regarding off-road recharging infrastructure, fuel prices, EV market share and driving range. Other, less conservative, scenarios could be considered for further research, in particular with respect to fuel prices. Second, this study is conducted under the assumption that the travel patterns and route selection are rational and known. A beneficial future line of research would be to incorporate uncertainty as well as bounded rationality into the model. Third, the current study is conducted under the assumption of population homogeneity - for example with respect to risk aversion. However, it would be beneficial to incorporate population heterogeneity within the decision-making processes related to recharging. Fourth, the current study assumes that the recharging stations do not have capacity constraints and that travelers do not learn from their previous recharging experience. Hence, it would be beneficial to incorporate both capacity constraints and learning experience by allowing feedback across decision models. In conclusion, the current study is based upon a single-technology demand function. However, the results indicate that it would be beneficial to explore data collection regarding travelers' preferences underlying the choice between competing recharging technologies - namely recharging time, the number of daily charging visits and charging costs.

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