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How many fast-charging stations do we need along European highways?

Patrick Jochem[a,b,*], Eckhard Szimba[c], Melanie Reuter-Oppermann[b]

[a] Institute for Industrial Production (IIP) at Karlsruhe Institute of Technology (KIT), Hertzstr. 16, D-76356 Karlsruhe, Germany
[b] Karlsruhe Service Research Institute (KSRI) at Karlsruhe Institute of Technology (KIT), Germany
[c] Institute of Economics (ECON) at Karlsruhe Institute of Technology (KIT), Germany

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ABSTRACT

For a successful market take-up of plug-in electric vehicles, fast-charging stations along the highway network play a significant role. This paper provides results from a first study on estimating the minimum number of fast-charging stations along the European highway network of selected countries (i.e., France, Germany, the Benelux countries, Switzerland, Austria, Denmark, the Czech Republic, and Poland) and gives an estimate on their future profitability. The combination of a comprehensive dataset of passenger car trips in Europe and an efficient arc-cover-path-cover flow-refueling location model allows generating results for such a comprehensive transnational highway network for the first time. Besides the minimum number of required fast-charging stations which results from the applied flow-refueling location model (FRLM), an estimation of their profitability as well as some country-specific results are also identified. According to these results the operation of fast-charging stations along the highway will be attractive in 2030 because the number of customers per day and their willingness to pay for a charge is high compared to inner-city charging stations. Their location-specific workloads as well as revenues differ significantly and a careful selection of locations is decisive for their economic operation.

1. Introduction

Climate change, oil dependency, and cities suffering from air pollution are severe challenges of our society and might lead to electrification of passenger road transport (Creutzig et al., 2015). The threat of the global car stock doubling from 2010 to 2050 accelerates this development (IEA, 2017). Furthermore, the current fast development in battery technology (Schmidt et al., 2017) increases the aspiration for a market uptake of plug-in electric vehicles (PEV). Only perceived range anxiety of non-users and high investments in the car and charging stations still seem to hinder a breakthrough in market penetration of PEV (Franke et al., 2017). Furthermore, the vehicle supply by the automotive industry, which still limits their production of PEV and offered models of PEV, is still thwarting the market breakthrough.

Current research shows that the number of required public charging stations has been overestimated. Fleet studies indicate that current chargings of privately used cars occur mainly at private homes or at workplaces (Figenbaum and Kolbenstvedt 2016; Hardman et al., 2018) and in the future also during shopping at semi-private charging stations. For commercial fleet vehicles,

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* Corresponding author at: Institute for Industrial Production (IIP) at Karlsruhe Institute of Technology (KIT), Hertzstr. 16, D-76187 Karlsruhe, Germany.

E-mail address: jochem@kit.edu (P. Jochem).

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chargings occur mainly at the premises of their company (Schäuble et al., 2017; Ketelaer et al., 2014). Hence, the requirement for public charging stations focuses mainly on long distance trips, and therefore along the highway network (cf. Jochem et al., 2016a).

The following research is focused on publicly accessible fast charging stations (FCS), which differ according to the international standard IEC 61851 from usual public AC (alternating current) charging stations (i.e., Mode 3, usually up to 22 kW charging). These Mode 3 charging stations might mainly be located in city centers next to shopping malls, workplaces or leisure facilities. FCS (i.e., DC (direct current) Mode 4, currently 50 or 150 kW charging, and in the future up to 350 kW charging) are most suitable to be positioned along highways in order to enable long-distance trips by PEV. While the Mode 3 charging stations have only few customers a day with low willingness-to-pay (due to other alternatives), FCS along the highway can serve several dozens of customers with a high willingness-to-pay (due to the lack of alternatives, cf. Serradilla et al., 2017). Hence, the financial support by the government for the allocation of FCS should be limited in time, and an “over allocation” of FCS correlates significantly with lower profitability as it creates alternatives and decreases the workload (i.e., energy demand) per FCS (Jochem et al., 2016a, 2016b). However, for the early market years, the strategy of “over allocation” might accelerate the uptake of the PEV market by overcoming the well-known range anxiety of early PEV users.

The transport policy of the European Union (EU) supports the market penetration of PEV by the Directive on the deployment of alternative fuels infrastructure (EU, 2014). While the regulation on the Trans-European Transport Network (TEN-T) promotes the evolution of low-carbon transport infrastructure, the Connecting Europe Facility (CEF) (EU, 2013) provides the financial framework to support such investments. In 2014, the European Parliament passed a legislative resolution (European Parliament, 2014) for a sufficient number of charging stations for PEV to become available by 2020.

In this political context, the current paper focuses on two research tasks. First, the minimum number of FCS along the highways for covering all long-distance trips in the considered region by PEV with a range of 150 km is calculated. Second, the profitability of these FCS is estimated. The combination of these two research questions leads to further policy recommendations on where and how many FCS are to be allocated along the European highway network. The paper addresses long-distance trips in France, Germany, the Benelux countries, Switzerland, Austria, Denmark, the Czech Republic, and Poland.

Consequently, the remainder of this paper is as follows. After a short overview of related work in the next section, all input data, i.e., volumes of passenger car trips per origin-destination (O/D) pair, is described. Then, the applied model is presented and the resulting findings are displayed and discussed. Finally, the conclusion derives main policy implications.

2. Related work

There are several studies for estimating the number of required charging stations for a complete coverage of all-electric flows in different regions. From a methodological point of view, there is a strong relation to the research field on minimizing the number of (alternative) fuel stations or other logistics-related work (cf. Adler and Mirchandani, 2017). The literature on this topic can be mainly differentiated between (1) the development of sophisticated theoretical optimization models (see below), (2) extending these models by considering queuing effects at the FCS, and (3) “ad-hoc” models, such as placing FCS at each motorway station (cf. Reuter-Oppermann et al., 2017) which are not considered in the following.

The Maximal Covering Location Model by Church and ReVelle (1974) provides a basis for theoretical optimization models for minimizing the number of service stations for alternative fuels along the highway system. Hodgson (1990) extends former models by maximizing the covered flows. The second significant extension is provided by Kuby and Lim (2005) and their flow-refueling location model (FRLM), which considers several refueling stops during long distance trips and maximizes the number of covered trips (trip perspective). However, the developed algorithm is computationally expensive and therefore impractical for realistic networks of moderate or larger sizes such as the European highway system. Consequently, Lim and Kuby (2010), Capar and Kuby (2012), and Capar et al. (2013) developed and applied heuristics to solve the FRLM in an acceptable time for larger networks. Jochem et al. (2016a) applied this model to the southern German autobahn network in the states of Bavaria and Baden-Wuerttemberg and proved the high efficient formulation of the arc-cover-path-cover (AC-PC) FRLM. He et al. (2019) show an FRLM application to a reduced US highway network of 3940 O/D pairs for different electric ranges. Extensions of these models are e.g., the dynamic evaluation of fast-charging networks (cf. Sathaye and Kelley, 2013, or Chung and Kwon, 2015), the application on roundtrips of trucks (cf. Hwang et al., 2017), a consideration of national partial country coverage constraints in order to increase the covered ton-kilometers in Europe (Kuby et al., 2017), an impact analysis of the electricity system (Jochem et al., 2016b), or a parallel optimization of battery size (cf. Nie and Ghamami, 2013). Tran et al. (2018) developed an efficient heuristic algorithm, which needs less computing time than the original FRLM and applied it to different case studies with up to 1000 nodes.

More recent approaches consider queuing effects in front of FCS and therefore optimize the capacity of each FCS, too. Upchurch et al. (2009) introduced the Capacitated Flow Refueling Location Mode (CFRLM), which defines capacity in interchangeable modular units. The main difference to the original FRLM is that the location variable is not binary but an integer, meaning that multiple modules (i.e., charging point) can be located at the same location (i.e., charging location). Correspondingly, besides the constraint of limited locations, the number of charging points per FCS is restricted, too. This is already considered in Capar et al. (2013) as well as Hosseini and MirHassani (2015). The latter formulated the Capacitated Recharging Station Location Model with Queue (CRSLM-Q), which considers a multitude of factors such as capacity, construction costs, waiting times and queue sizes. However, due to its complexity, the CRSLM-Q cannot be applied to networks of moderate or large size. Similarly, Hosseini et al. (2017) developed the capacitated deviation-flow refueling location problem (CDFRLP) based on a mixed integer linear program (MILP) and a heuristic in which the number of vehicles refueled at each FCS is limited and customers are assumed to deviate from their pre-planned routes when required. They applied their method to different artificial networks. Xiang et al. (2016) also combined an optimization approach with a queuing model and applied the developed tool to the Sioux Falls transportation network. Yıldız et al. (2016) extended the flow maximization problem by considering the routing of individual vehicles, too. The authors applied their model to an artificial 25-node network of the Chicago metropolitan area (Simchi-Levi and Berman, 1988).

Research on the profitability of FCS is still in the fledgling stages and the results are highly uncertain. While Schroeder and Traber (2012) were rather pessimistic on the profitability of FCS in 2011 for Germany, Serradilla et al. (2017) gave a more optimistic outline based on empirical data from FCS usage and PEV users in the UK. Morrissey et al. (2016) indicated in an empirical study with 711 monitored charging points in Ireland that FCS are going to be profitable sooner than slower charging stations, and that FCS are more attractive for current customers than usual charging stations. This has been confirmed by Helmus et al. (2018). Madina et al. (2016) developed business models for operating charging stations with a morphological box-based approach and made outlines for the profitability of charging stations for Spain, Germany, and The Netherlands. According to their study, other additional services (e.g., advertising at the FCS or a nearby restaurant) might help to make the FCS a profitable business case in the early market phase. They expect high synergies between the profitability of FCS and nearby restaurants. Muratori et al. (2019) focus on the co-location of photovoltaic panels and energy storages with FCS and indicate a decrease of electricity costs for PEV users for all considered locations in the United States. Funke et al. (in press) show, however, that local storages in combination with FCS are not yet profitable.

In conclusion, there is no model in literature so far which estimates the profitability of operating FCS based on their optimized number, location, and dimensioning for a larger empirical highway network. In the following, the applied data and FRLM is introduced for calculating these profitability estimates of FCS for the highway network of selected European countries by giving an outlook on potential revenues.

3. Volumes of passenger car trips per O/D pair

For the model calculations, the two following main datasets are required. First, the flow data of all long-distance trips on the European highway system are used for representing the demand, and second the technical restrictions of the PEV and FCS are considered in the constraints of the optimizing model.

The demand data underlying the calculations stem from the ETISplus project, which has been funded under the European Union's 7th Framework Programme (Newton et al., 2013). Among others, ETISplus embraces Europe-wide and transport mode-specific demand data at the level of O/D matrices. The underlying regional dataset includes all NUTS-3 regions and considers about 2.5 million O/D pairs. The methodology applied for the generation of the passenger O/D matrices follows largely the classical "four-step" approach of transport demand modeling (cf. Szimba et al., 2013). In the first step, the trip generation, the number of trips are estimated for each modelling zone (NUTS-3 region) and each trip purpose (business, holiday, private), based on regional socio-economic data and trip rates obtained from travel surveys. In the second step, the trip distribution, the share of trips which are estimated to have their destinations outside the origin zone, is distributed to other regions, based on the destination regions' attractiveness, travel impedances between the origin and the destination, and trip length distributions. In the third step, the market shares of the main transport modes are calculated for each O/D pair, under consideration of transport mode-specific user costs. Finally, the estimated trips per transport mode are assigned on the road, rail, and air networks, under the assumption that routes with minimum user costs are chosen. The traffic volumes obtained at the level of network links are calibrated to traffic count data.

In order to identify those O/D pairs which use a motorway link, all road passenger O/D pairs are assigned to the updated ETISplus road network model (see Fig. 1) by applying the Dijkstra algorithm (Dijkstra, 1959) under the assumption that the fastest route is chosen. The updated ETISplus road network model consists of more than 58,400 links and 43,300 nodes. As this work focuses on long-distance trips in France, Germany, the Benelux countries, Switzerland, Austria, Denmark, the Czech Republic, and Poland, only O/D pairs in or between these countries with a length of at least 100 km are considered for further analysis. Hence, all O/D pairs whose origin and destination are located in the considered countries, whose length is at least 100 km, and which use at least one motorway link on the fastest route between their origin and destination are selected from the database. For these selected O/D pairs the distances on the assigned fastest route are computed for the route between the origin region's feeding node to the motorway access, the distance on the motorway system covered, and the distance between the motorway egress and the feeding node of the destination. The scope of selected O/D pairs also embraces those relations, which enter the motorway system several times on their optimal routing through the network (e.g., feeding node origin – access motorway – motorway – egress motorway – other roads – access motorway – motorway – egress motorway – feeding node destination). In order to extrapolate the passenger transport demand and the overall vehicle stock to the years 2020 and 2030, the baseline forecasts of the HIGH-TOOL model (Szimba et al., 2018; Szimba, 2016), as well as the predictions of the EU Reference Scenario 2013 (European Commission, 2013) have been used. The selected O/D pairs' distances, differentiated by total distance and distance on motorways covered, as well as the modeled volumes, serve as input for our model described in the following chapter.

With regard to the technical data of PEV and FCS, a PEV market share of 1% for all countries under consideration is assumed for 2020. For 2030, country-specific values are supposed: 10% for Czech Republic, Poland, and Germany, 15% for France, Switzerland, Austria, as well as Denmark, and 20% for Belgium, the Netherlands, and Luxembourg. While the future development of driving ranges is not foreseeable yet and the fuel consumption depends on several circumstances such as travel speed or temperature, the minimum distance between FCS is assumed to amount to 150 km.

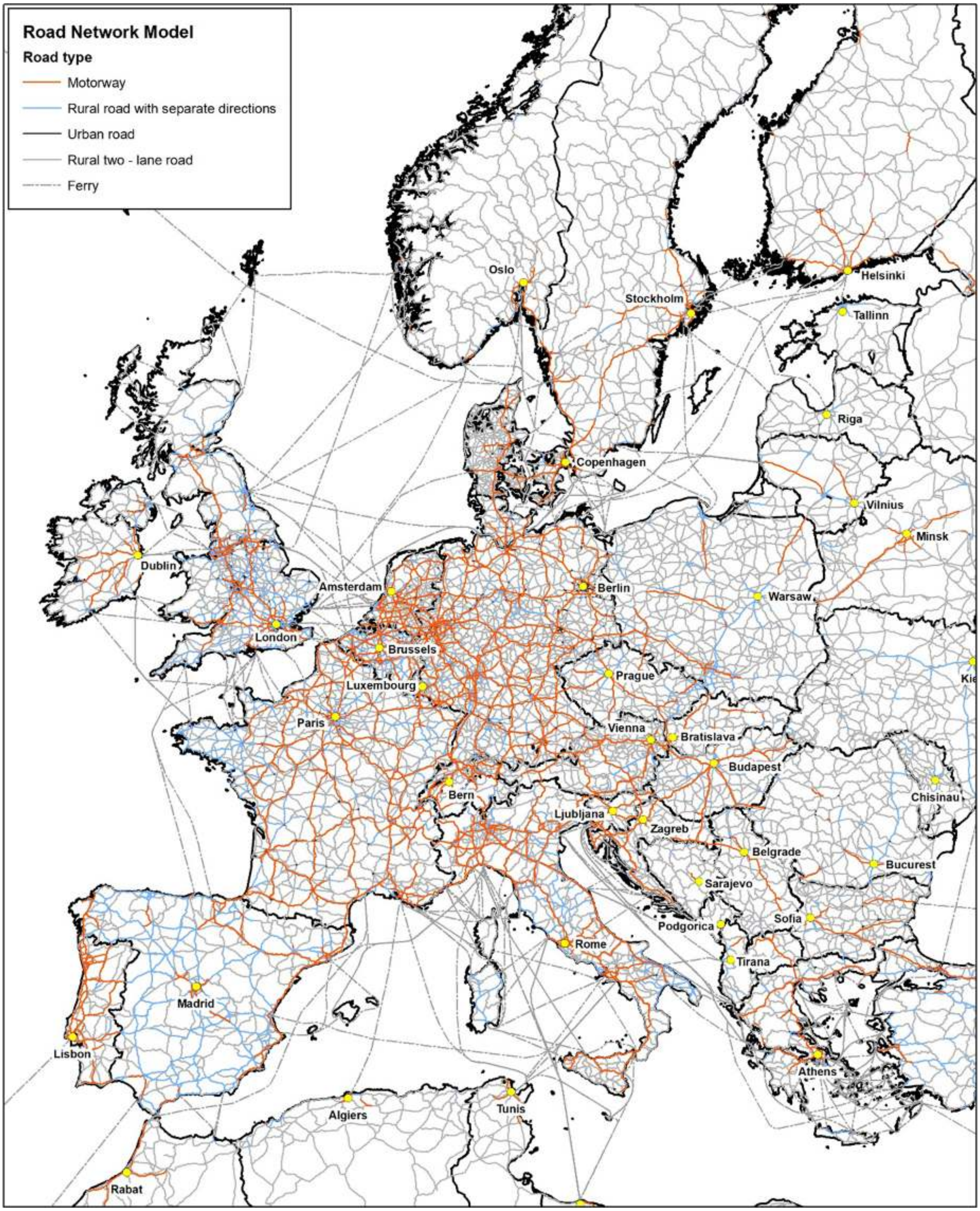
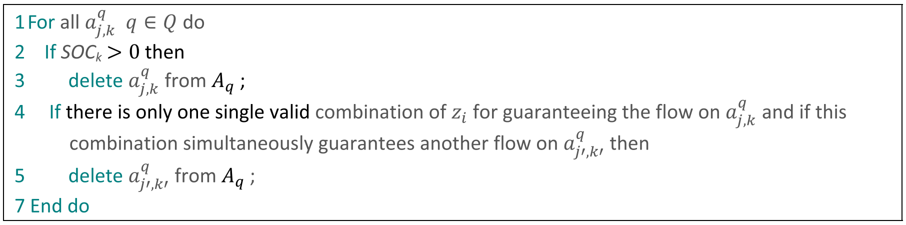


Fig. 1. Road network model applied for route choice modeling.

4. Optimizing location model

For the mathematical model, the FRLM is chosen which minimizes the required number of FCS for a given network (e.g., Capar et al., 2013). We then select a set of possible locations along the highway network, which are provided by the network model's nodes (i.e., mainly all highway exits and toll stations) and take the O/D flows along the highway network from Section 3 above. Jochem



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1 For all $a^q_{j,k}$  $q \in Q$ do
2   If $SOC_k > 0$ then
3       delete $a^q_{j,k}$ from $A_q$ ;
4   If there is only one single valid combination of $z_i$ for guaranteeing the flow on $a^q_{j,k}$ and if this
      combination simultaneously guarantees another flow on $a^q_{j\prime,k\prime}$ then
5       delete $a^q_{j\prime,k\prime}$ from $A_q$ ;
7 End do
```

Fig. 2. Pseudo code of the improved algorithm for reducing the set of necessary arcs for FRLM.

et al. (2016a) have already successfully applied the formulation to the problem of locating FCS along the highway in southern Germany. They and other authors, however, were limited by computation capacities. Therefore, after the general description of the FRLM, an efficient algorithm is introduced, which allows applying the FRLM to more comprehensive networks.

The FRLM assumes a set of nodes representing potential locations denoted by N. A set of directional arcs A between the nodes represent the highways. Together, nodes and arcs constitute a network $G = (N, A)$. Arcs $a_{j,k} \in A_q$ between a starting node j and an ending node k form a path $q \in Q$ represent an O/D pair. All relevant O/D pairs of paths are stored in the set Q. Another parameter is the traffic volume f_q on a path $q \in Q$. $K^q_{j,k}$ denotes the subset of candidate locations (i.e., nodes), which enables to cover the arc $a_{j,k}$ on A_q with the given range limitation. These subsets $K^q_{j,k}$ are computed beforehand. It is assumed that each trip (also returns) starts with a completely recharged vehicle (which simplifies the consideration of round trips). The binary decision variable y_q is equal to 1, if the flow on path $q \in Q$ can be recharged by using the located stations (i.e., there is at least one station within the vehicle range along this whole path), 0 else. The second binary decision variable z_i is equal to 1, if a charging site is built at node i and 0 else.

The formulation is as follows:

$$\min \sum_{i \in N} z_i \tag{1}$$

$$\text{s. t.} \quad \sum\nolimits_{i \in K^q_{j,k}} z_i \geq y_q \quad \forall\, q \in Q,\, a_{j,k} \in A_q \tag{2}$$

$$\sum_{q \in Q} f_q \cdot y_q \geq S = s \cdot \sum_{q \in Q} f_q \tag{3}$$

$$y_q,\, z_i \in \{0, 1\} \quad \forall\, q \in Q,\, i \in N \tag{4}$$

The objective function (1) minimizes the total number of FCS to be opened. Constraints (2) assure that a flow is only labeled as recharged if every directional arc of each path q can be successfully crossed considering the battery capacity and the located facilities. Constraint (3) ensures that at least the percentage s of the flows is covered by the opened charging stations. Note that for this work we set $s = 100\%$. Constraints (4) are the domain constraints for the two sets of binary decision variables.

As a methodological extension to Jochem et al. (2016a) the preselection method of data was improved by using an efficient algorithm to determine the reduced subset $K^q_{j,k}$. It is based on the ideas of Kuby and Lim (2005), but the actual implementation of the algorithm reduces the required number of candidate locations significantly before the optimization begins and consequently reduced the computational effort substantially. Fig. 2 gives a short overview of the developed algorithm. Here, $SOC_k$is the State of Charge at the destination (including access and egress distances). There are two important aspects of the approach. First, remove all (short) arcs where the destination can be reached without recharging (lines 1–3). Second, redundant arcs, i.e., arcs that are complete supersets of any other arc, are identified and removed (lines 4 and 5). To give an easy example: if there is an arc $a_{j,k}$ from node i_j to node i_k with only one candidate location in a node i_2 which allows to reach i_k (i.e., z_i must be 1); and if there is another arc $a_{j,k'}$ (e.g., with only a very short distance between the two nodes i_k and $i_{k'}$) which can be covered by using the FCS at i_2. Then $a_{j,k'}$ is redundant and is deleted. Finally, we reduced the number of arcs by limiting our analysis only to flows with more than 5000 cars per year, which reduces A_q (and the number of constraints) considerably.

This improved algorithm reduces the number of relevant arcs and therewith $K^q_{j,k}$and the problem size, which makes the FRLM solvable by a standard ILP solver (IBM CPLEX) on a conventional computer (Intel Core i7-3770K @ 3.50 GHz, 16 GB DDR3-RAM and Windows 10 64 bit) in a reasonable timeframe of five hours. This is a considerable success as the network size increased by a factor of 10 compared to Jochem et al. (2016a) who stated already computational challenges. Even an extension to other counties (e.g., Italy, Spain or UK) should be still in the scope of current computational possibilities. Hence, this algorithm makes the optimisation more efficient and allows applying FRLM to significantly more extensive networks.

The station minimizing FRLM provides a lower-bound of necessary charging stations within a network for a specific vehicle range. Consequently, the workload at each FCS within this optimized network is an upper-bound as more FCS would lead to fewer volumes at individual FCS. In order to estimate the number of charging points per optimal allocated FCS a simple agent-based queuing model from Jochem et al. (2016b) is applied. We assumed that at each location for an optimally allocated FCS the local infrastructure is sufficient (i.e., there are sufficient parking lots, suitable rest area, connection to the electricity grid, etc.).

5. Results and discussion

The resulting workloads from these optimal allocated FCS along the highway network of the selected European countries are displayed in Fig. 3 for the year 2030. The highest number of charging stations is expected for Germany (128), while the charging stations with the highest workload (up to 5000 charging services per day) are located in France. This pattern is due to different densities of the motorway networks and partly also due to the higher PEV market share in France. Since Germany has a denser motorway network than France, a higher number of charging stations are required with comparatively lower demand. Even though Italy is not part of our investigation, some charging stations are located in the northern part of Italy because of transit trips, mainly between the southern part of France and Switzerland, Austrian and German regions (cf. Kuby et al., 2017).

The sparse allocation of FCS leads to a diverse distribution of loads at the FCS. On average more than 100 (1000) customers per day per FCS in 2020 (2030) are expected and in 2030 up to 200 PEV arrivals per hour at an FCS with 30 charging points during Friday afternoons can be expected (cf. load-peak in Fig. 4). When the average energy demand is 15 kW h and the charging rate equals 150 kW (i.e., the charging time is 15 kW h/150 kW = 0.1 h), the resulting waiting times are still negligible: In this case, and under the assumption that PEV arrival rate is equally distributed within an hour, 20 PEV arrive each 0.1 h, which can be easily served at the 30 charging points – on average. The resulting high power demand per FCS (e.g., 150 kW*30 charging points = 4.5 MW) shows that the power demand by these locations might be substantial and the local grid connection should be carefully designed. More locations would lead to fewer charging events per FCS and hence, a lower grid impact.

Correspondingly, the electricity demand differs considerably among the FCS (cf. Table 1). The 22 locations with the highest energy supply in these countries cover about 30% of the overall electricity demand while the last 100 FCS share only about 1% altogether. In Germany, the 22 most frequently used FCS provide on average more than 15 MW h per week. For the 20 least frequently used FCS in 2020 this value does not exceed 5 MW h/week. Consequently, the ratio of customers per charging point declines

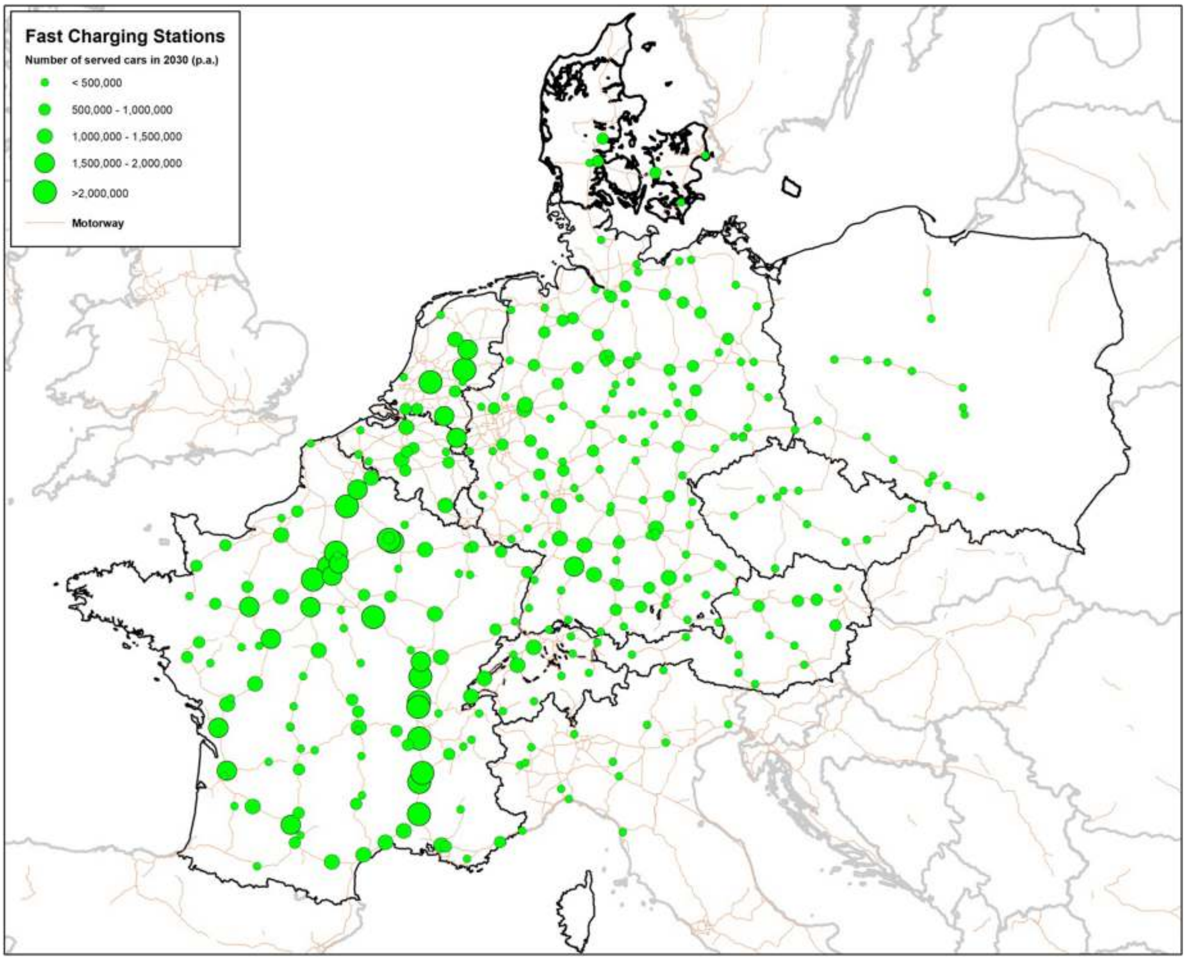

Fig. 3. Minimum number of FCS and expected demand for 2030.

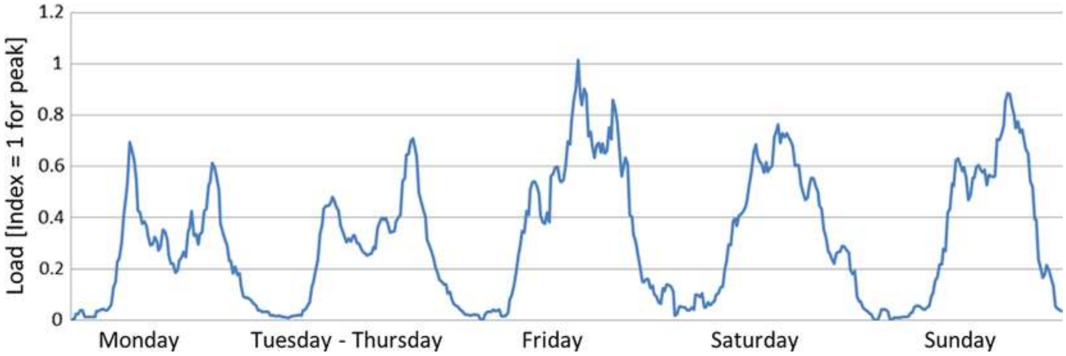

Fig. 4. Load pattern from PEV fast-charging at highways (based on Jochem et al., 2016b).

Table 1
Country-specific electricity demand at FCS and estimates for revenues per FCS.

Country	Model Input						Model Output			
	Mileage 2020 [billion pkm]	Mileage 2030 [billion pkm]	PEV share 2020	PEV share 2030	Electricity Demand 2020 [GW h/a]	Electricity Demand 2030 [TW h/a]	No of FCS 2020 (avg. no. of points/ FCS)	No of FCS 2030 (avg no. of points/ FCS)	Electricity demand per FCS 2020 [MW h/FCS/a]	Electricity demand per FCS 2030 [GW h/FCS/a]
Germany	915	922	1%	10%	183	1.84	128(5)	128(20)	1430	14.4
Be-Ne-Lux	280	301	1%	20%	56	1.20	22(5)	22(25)	2545	54.7
France	768	849	1%	15%	153.6	2.55	104(5)	104(30)	1477	24.5
Switzerland	92	98	1%	15%	18.4	0.29	12(5)	12(8)	1533	24.5
Austria	78	84	1%	15%	15.6	0.25	15(5)	15(8)	1040	16.8
Czech Republic	73	84	1%	10%	14.6	0.17	10(5)	10(2)	1460	16.8
Poland	355	401	1%	10%	71	0.80	17(5)	17(2)	4176	47.2
Denmark	53	56	1%	15%	10.6	0.17	6(3)	6(3)	1767	28.0

and makes these FCS less profitable – especially in the early market phase of PEV. Hence, the profitability for the latter is still questionable but might be cross-subsidised from other FCS.

Daring a rough estimation of a profitable operation of these FCS, we start with the average electricity demand per FCS in 2030, which is about 14 GW h for Germany. Hence, if a surcharge per kWh of 0.05 euros is assumed, the marginal return per year in 2030 amounts on average to 0.7 million euros per FCS for Germany and 2.7 million euros for France. These values exceed current cost estimates of FCS significantly. Serradilla et al. (2017) give estimates for capital expenditures (CAPEX) of about 50,000 euros per FCS for usual workloads (i.e., with up to four charging points). Even if we assume a CAPEX of 300,000 euros for our oversized FCS with about 20 charging points, an amortisation time of eight years, and an interest rate of 5%, an annual cost estimate of about 45,000 euros per FCS emerges. While Medina et al. (2016) are more optimistic with their results, Zhang et al. (2018b) indicates costs of these oversized FCS of about a million euros, which would increase our annual cost estimate to about 150,000 euros per FCS, which is still well below the marginal returns of 0.7 million euros, as mentioned above.

Concluding, despite the questionable profitability of usual public charging stations in cities (cf. Zhang et al., 2018a) the operation of FCS along the highway seems to be more attractive from an economic point of view – especially if people do not block the FCS longer than the charging process lasts (cf. Motoaki and Shirk, 2017). Hence, reserving attractive locations today by placing (still uneconomic) FCS might be a good strategy for ensuring good positions in the future attractive fast-charging market.

Compared to the current deployment of FCS in 2018, our results from the FRLM of 128 FCS for Germany seem absurdly small. Today only a single platform provides already 315 FCS along the German highway network (Tank und Rast, 2018) and on the European average, we see already almost 25 FCS per 100 highway kilometers (EAFO, 2018). Hence, the reality already created a situation, where we have (theoretically) more than enough FCS, which however does not necessarily provide a sufficient number of charging points per location.

Compared with results from other studies, the 314 FCS for our network is comparable to the 250 FCS for the US network estimated by He et al. (2019) and our estimated number of fast-charging points per 1000 BEV for Germany of about 0.7 (2560/4,000,000) is in a similar range as the numbers by Gnann et al. (2018) with 0.7–1. An advantage of the relatively low number of optimally allocated charging stations is that the law of large numbers leads to a higher utilization rate per charging point compared to a solution with more locations, which results in a higher profitability per charging point.

Our results depend on several assumptions and are first estimations of the profitability. Nevertheless, as the high net earnings already indicate, the business case of operating FCS along the highway is appealing. Also further sensitivity analyses confirm these insights. For instance, an increase of range to 200 km, which seems to be reasonable when considering current PEV models with an average range of 300 km, leads to decreasing numbers of required FCS from 314 to 210. 64 FCS are selected in both cases. These seem to be very attractive locations, which show in average higher energy demand values. Another technical assumption is the charging power, which is currently restricted from the vehicle to about 50 kW, while FCS already provide 150 kW. It is probable that at least PEV, used for long-distance trips, may have the option for higher charging loads, this is why we assumed 150 kW in average for 2030. Lower charging rates would lead to longer waiting times and correspondingly to further investments of FCS operators in charging points. This would result in a decreasing profitability. Finally another uncertainty in our calculation is the market share on PEV on these long-distance trips. Our estimated share of PEV between 10 and 20% in 2030 seems to be rather optimistic from the current perspective, even though other scenarios show much more optimistic values (e.g. the EV30@30 Scenario from the IEA, 2018). Small deviations from these numbers might not influence our results. Operators should certainly observe the market deployment and adapt their investments accordingly.

The main limitations of our modeling are the limited geographical scope and the correspondingly reduced number of considered O/D pairs, and the focus on trips which are routed on highways only, thus excluding dual carriageway roads, expressways, as well as local traffic (cf. Gnann et al., 2017; Kelley, 2017). A further limitation is the underlying modelling approach: traffic demand is represented by flows between the central node of the origin region and the destination region. This involves inaccuracies for inter-zonal transport relations whose origin or destination is located away from the regions' centers (cf. Ihrig, 2018). Furthermore, it is still unclear whether PEV users feel comfortable with a FCS network that provides charging facilities only every 150 km. Range anxiety might lead to the desire of a denser FCS network, such as our current service station network along the highway. This might, however, decrease the profitability of FCS – especially during the early market years of PEV market diffusion.

6. Conclusion and policy implications

For a successful uptake of the PEV market, FCS along the highway network play a significant role. The data for the highway network of the considered European countries together with an efficient optimizing tool allows estimating the minimum number of FCS that cover all flows in the system and therefore yield to a benchmark of an FCS network at lowest costs and highest profitability. Our innovative method allows for the first time to apply this optimization task for a transnational problem.

Core results are that for 150 km range-limited PEV (in theory), only 314 FCS suffice in order to cover all passenger car flows within the regarded geographical scope – much fewer than already in operation in 2018. This scarce allocation leads to significant workloads at each FCS and correspondingly a profitable operation in the future. However, the workload is highly unequally distributed between these charging stations, which makes the choice of location for FCS providers significant and an early allocation of FCS at attractive locations reasonable (even though their operation is still not profitable). Hence, policy measures for the allocation of FCS should take this into consideration by fostering an equal distribution of FCS along the highway – e.g., by subsidizing unattractive (but necessary) locations. At attractive locations, subsidies should be critically reconsidered and an "over allocation" of FCS is negatively correlated with the profitability of operation. The number of 314 FCS for our considered region is by far a lower-bound benchmark and for practical reasons as well as range anxiety should lead to much higher numbers in reality.

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