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Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany

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HIGHLIGHTS

- Applies over 400 real-world driver data from German commercial vehicles (LDV).
- Quantifies cost-efficiency of longer battery ranges & fast charging infrastructure.
- Fast-charging infrastructure increases utility of many drivers and is cost-efficient.
- Longer ranges are needed for high BEV fleet shares.

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ABSTRACT

To reach ambitious CO_2 mitigation targets, the transport sector has to become nearly emission-free and the most promising option for passenger cars are battery electric vehicles (BEV) powered using renewable energy. Despite their important benefits, BEV still face technological barriers, mainly their limited battery range and the limited availability of public fast-charging infrastructure. These factors are hindering the diffusion of electric vehicles (EV). The question of how to address these technical barriers has been widely analyzed in the literature, but so far there has been no cost-efficiency comparison of longer battery ranges and more widespread fast-charging infrastructure that evaluates them both technically and economically. This paper aims to find cost-efficient ways to address limited battery ranges and availability of public fast-charging infrastructure. We focus on German passenger cars that are licensed to commercial owners, since these are an important first market for EV. Our results indicate that fast-charging infrastructure is very cost-efficient as it enables significant proportions of BEV in the fleet at low infrastructure density. The technically feasible maximum BEV shares in the commercial sector can only be achieved with longer battery ranges. However, longer battery ranges are currently associated with comparatively high additional costs.

1. Introduction

Battery electric vehicles (BEV) are an important option to reduce greenhouse gas emissions (GHG) from the transport sector [1] which is necessary to reach ambitious European [2] but also global GHG emission targets [3]. However, the diffusion of BEV is limited, mainly due to the economic barrier of high purchasing cost and the technical barriers of low battery range as well as insufficient availability of charging infrastructure [4]. The deployment of fast-charging networks and the development of longer vehicle ranges can be regarded as complementary or even substitutable, since they both directly affect the daily distances possible with a BEV. Accordingly, potential interaction effects have to be taken into account when assessing policies to support the diffusion of BEV, especially as the effect of longer battery ranges on the demand for fast-charging infrastructure (FCI) is not straightforward. On the one hand, long-range BEV may reduce the need for public charging since home charging might be sufficient for most of the trips, even longer trips. On the other hand, long-range BEV could be used more and more for long-distance trips, thus increasing the demand for public FCI.

The most important current policies to foster the diffusion of electric vehicles (EV) are purchase incentives [5] and the (subsidized) construction of public FCI [6]. Policies addressing the high purchase cost of EV are rarely designed to subsidize longer vehicle ranges directly, although the VAT or purchase tax exemptions depend on the resale value of the vehicle, which does increase with longer vehicle ranges. Charging

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infrastructure requires large upfront investments and has a long lifetime. Both options address the limited driving distances of BEV but both are expensive and it remains unclear which is the more cost-efficient option. Accordingly, these two options - longer battery ranges and the deployment of fast-charging infrastructure (FCI) - need to be compared in a cost-efficiency analysis.

1.1. Literature review and scope of this study

Evaluating the most cost-efficient means to address the limited range of BEV comprises three main aspects: First, determine the effectiveness of the different options. Second, quantify the resulting need for public FCI. Third, compare the cost of developing charging infrastructure with the cost of extended battery ranges. To date, these three aspects have not been synthesized together in the literature.

The question of how well BEV can meet today's driving needs has received broad attention in the literature. One group of studies is based on the driving behavior reported in household travel surveys. These datasets are advantageous due to their large sample sizes. For example, Zhang et al. [7] analyzed 20,295 vehicles of the US-American National Travel Household Survey (NHTS) and found that 88% of these could be operated as a BEV assuming a 60-mile (∼100 km) electric range as well as only home charging. However, the limited observation period of the datasets used in these kinds of studies tends to overestimate the suitability of BEV because long-distance trips are underrepresented (e.g. [8]).

A second group of studies estimates the distribution of user-specific daily driving distances to identify the share of days with trip distances exceeding potential BEV ranges. Accordingly, Weiss et al. [9] combined different datasets to analyze the average driving behavior of German vehicles over one year. The authors found that the daily trips of almost 30% of the vehicles are less than 100 km on all days of the year except for four days. According to Plötz [8], however, who conducted a comparable analysis, 35% of German car users drive more than 100 km on at least 20 days per year.

A third group of studies focuses on GPS data for in-depth analysis of BEV driving (see Table 1). These studies often find that BEVs have a high technical potential to electrify an individual's trips. Pearre et al. [10] analyzed the driving data of 484 vehicles in the US with an average observation period of 50 days and found that 9% of users never exceed 100 miles (∼160 km) in one day (and 21% never exceed 150 miles). Accordingly, Neubauer and Wood [11] concluded that 75% of the yearly vehicle kilometers traveled could be performed with a BEV with an electric range of 75 miles (120 km) and no public charging infrastructure. The availability of public fast charging infrastructure could raise this share up to 90%. The authors used the Puget Sound Regional Council's 2007 Traffic Choices Study, a database of 317 vehicles with an average observation period of one year. The aforementioned studies often focus on the vehicle user perspective.

In contrast, studies analyzing FCI needs that use actual driving data often base their analysis on fixed user-independent vehicle ranges. For example, Jochem et al. [12] used travel data to locate optimal charging sites along the German autobahn network. Zhang et al. [13] performed a comparable analysis for California. For city areas, the optimization of charging sites is an important factor to guarantee grid stability [14]. However, since we focus on FCI along German highway corridors, the question of grid stability is not within the scope of this study. Another common goal of FCI deployment analyses is to reduce the number of unfulfilled trips if all vehicles were BEV. Dong et al. [15] simulated driving and charging behavior based on GPS data around Seattle, assuming a fixed range of 100 miles for the whole fleet. Wood et al. [16] analyzed the effect of different FCI deployment scenarios on the number of achievable electric miles traveled for a fixed range of 75 miles for all vehicles. Since the use of detailed local travel or road data is computationally intensive [17], these kinds of studies are often limited to cities or larger metropolitan areas. Finally, studies addressing the cost of charging sites are often theoretical and do not consider the charging demand of individuals. For example, Jabbari and MacKenzie [18] examined the tradeoff between availability and the cost of a charging station using a queuing model without considering real-life cases.

While there are detailed studies of the technical potential of EV at user level and studies of an EV fleet's demand for FCI, a synthesis of both perspectives has only been achieved to some extent (Table 1). Wood et al. [19] analyzed different FCI deployment scenarios by assuming specific charging sites. The authors found that increasing the vehicle's electric range to above 100 miles had a comparable effect to deploying public fast-charging infrastructure with regard to the overall electrification potential of the analyzed vehicle fleet. Since the study analyzes specific charging sites, it is limited to a regional scale. Further, even though the study compares the effectiveness of FCI deployment and larger battery sizes, it was not designed to compare the cost-efficiency of these two parameters. For example, the density of the FCI network was not adapted to different battery ranges or different charging power. Accordingly, it was not possible to evaluate the most cost-efficient combination of FCI deployment and vehicle range, especially for individual users. In a comparable analysis, Nicholas et al. [20] found that charging sites are located further away from home for longer vehicle ranges. The authors analyzed the number of charging events needed for all charging sites in detail. However, because the analysis was limited to the regional level and did not include the temporal availability of FCI, it cannot answer the question of how longer vehicle ranges affect FCI requirements, particularly with a view to the widespread diffusion of electric vehicles. In addition, the analysis did not consider the effect of increasing the charging power on FCI needs, which is an important aspect for a cost-efficiency analysis. Most importantly, a cost analysis was not carried out within the framework of the study. The same conclusions hold for Wood et al. [21], who performed a comparable study for Massachusetts.

But for a cost-efficiency analysis, the cost of deploying charging infrastructure and the cost of longer battery ranges have to be compared and related to individual BEV suitability. Even though some of

Table 1
Literature overview.

Source	Technical BEV potential	Using individual vehicle ranges	Quantifying charging infrastructure	Cost analysis/cost comparison
Zhang et al. (2013) [7]	✓	X	X	X/X
Plötz (2014) [8]	✓	X	X	X/X
Weiss et al. (2014) [9]	✓	X	X	X/X
Pearre et al. (2011) [10]	✓	X	X	X/X
Neubauer, Wood (2014) [11]	✓	✓	X	X/X
Jochem et al. (2016) [12]	✓	X	✓	X/X
Zhang et al. (2015) [13]	✓	X	✓	X/X
Wood et al. (2015) [16]	✓	X	✓	X/X
Jabbari, MacKenzie (2017) [18]	X	X	X	✓/X
Wood et al. (2015) [19]	✓	✓	✓	X/X
Nicholas et al. (2012) [20]	✓	X	✓	X/X

the above-described studies analyzed costs, these focus either on only vehicle costs (e.g. [22]) or FCI costs (e.g. [18]) (see also Table 1).

To sum up, existing studies analyze the potential of either FCI deployment or extended vehicle range to electrify passenger transport, or examine the cost of one of these two instruments (see Table 1). There is no cost-efficiency comparison of individual vehicle costs and non-individual FCI costs, because these two options have not been modeled explicitly as complements or even as substitutes for increasing the electric daily kilometers travelled of EV.

The aim of this study is to close this gap and determine cost-efficient combinations of longer battery ranges and greater availability of fast-charging-infrastructure. Our study contributes to the literature by quantifying the cost and the electrification potential of FCI compared to longer battery ranges on national level. The novelty of our approach is that it combines all three steps mentioned above before. First, the technical suitability of BEV for today's driving needs was determined based on longitudinal driving data. Individual driving behavior was considered by modeling longitudinal dynamics as described in Section 2.1. Second, FCI needed for the geographical area of Germany (cf. Section 2.2) was identified based on the driving and charging behavior modeled in step one. The influence of different electric ranges on the required FCI was quantified with respect to the number of charging events as well as the charging time needed. Here, the focus is on fast-charging infrastructure, because slow public charging has a very limited effect on long-distance BEV trips [15,22]. Finally, the cost of longer battery ranges to deploying fast-charging infrastructure was compared as described in Section 2.3. The total cost of ownership were calculated in detail for every driving profile. This study does not aim to analyze potential BEV market shares in the future, but takes a long-term perspective and determines the additional cost for all the driving profiles that could be operated technically as BEV. Accordingly, our results indicate the level of subsidies necessary to compensate the additional cost of driving a BEV compared to a conventional car.

By identifying cost-efficient options to increase the daily range of EV for different vehicle and FCI specifications, our results contribute to the discussion concerning the selection of suitable investment strategies and funding policies for EV and fast-charging infrastructure and are therefore of potential interest to political and industrial decision-makers. Manufacturers of electric vehicles are already considering the development of their own fast-charging infrastructure and are increasingly having to decide how to balance investments in larger battery capacities on the one hand and in fast-charging infrastructure on the other hand. Our analyses show how individual users benefit from these measures and at which cost.

We focus on passenger cars licensed to commercial owners because these are an important first market for EV [23]. Commercially licensed vehicles comprise about two thirds of annual first registrations in Germany and they act as an important lever for their subsequent integration into the vehicle stock. In addition, the high annual kilometers traveled by such vehicles enable fast amortization of the higher investments in BEV [23]. The analysis is based on 467 driving profiles from commercially-owned German passenger cars. These are defined as all passenger cars registered to legal persons or public entities (because there is no official definition, cf. [23]). Commercially-owned passenger cars comprise both fleet cars and company cars [23]. The focus is on Germany as an important European passenger car market and a major player in the automotive industry worldwide [24].

2. Methodology

In this work, a techno-economic analysis was conducted, of how longer battery ranges and the availability of fast-charging infrastructure (FCI) could increase BEVs and at which cost. As already mentioned, the modeling logic is to evaluate the additional cost of BEV driving if technically possible and not to model the potential market uptake of BEVs. The research target is to quantify the potential share of BEVs and the additional cost of driving electrically compared to conventional driving for different battery ranges and FCI scenarios. We analyzed individual driving behavior, the resulting need for FCI and the overall costs for different vehicle designs and FCI availability within one model (cf. Fig. 1). This approach can analyze how longer battery ranges might influence user needs for fast-charging availability and vice versa. This aspect has not yet been addressed in the literature as far as we are aware. We present the different methodologies used for the individual modeling steps separately in the following sections.

2.1. Modeling technical BEV suitability

The first modeling step determines the potential of BEVs to meet user mobility requirements for different battery ranges as well different FCI availability. A BEV is assumed to be suitable if all of the observed driving days are within its driving range and if no more than 48 fast-charging events per year are required for long-distance trips. Accordingly, BEV suitability was determined in a two-step approach.

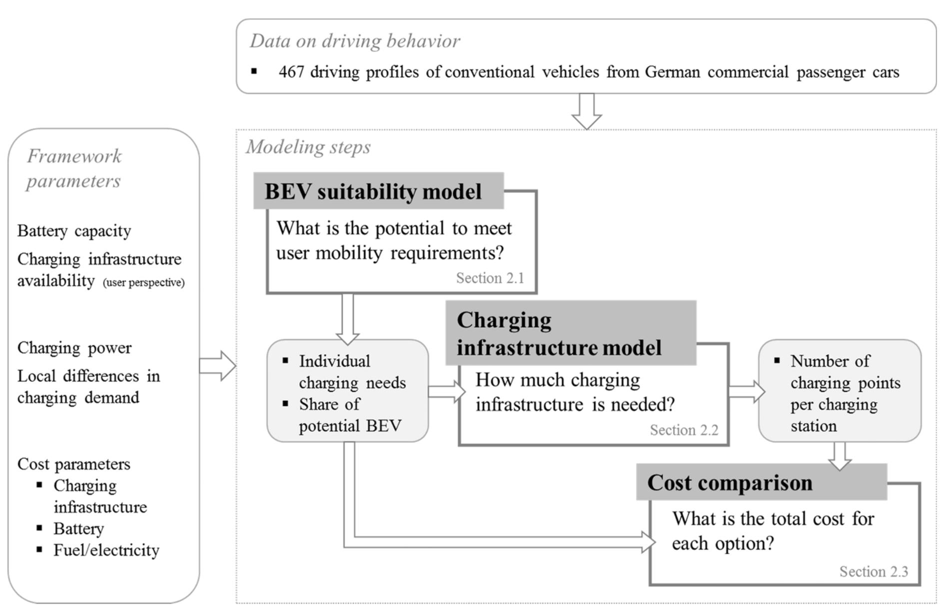

Fig. 1. Model overview.

First, the share of days within BEV range was determined by modeling longitudinal dynamics as described in Section 2.1.1. Such an individual analysis is necessary for every vehicle because driving varies widely between users regarding the daily distances traveled and the energy demand required [23]. Modeling the energy demand needed for driving at the level of individuals allows us to determine individual battery ranges and to account for the effects of a higher vehicle mass due to larger battery capacities. Second, as long-distance trips are underrepresented in driving data with a limited observation period [25], the number of fast-charging events per year was determined separately using a methodology developed by Plötz [8] (see Section 2.1.2).

The need for high suitability (100% of observed driving days and no more than 48 fast-charging events per year) was presumed because a BEV must be able to meet almost all the driving needs of a user to be considered an interesting alternative to a conventional vehicle in the long term. If weaker criteria were selected, BEV suitability would be even higher as discussed in Section 4.4.

2.1.1. Modeling individual driving

Electric driving was simulated individually for each driving profile because the distribution of driving energy demand as well as the BEV usage potential for every user were of interest. Individual driving energy demand was calculated based on longitudinal dynamics neglecting slope resistance [23]. The energy to overcome driving forces was calculated based on vehicle parameters and individual driving behavior as:

$$P_D = \left(\frac{1}{2}c_D\rho A v^2 + c_R mg + ma\right)*v. \tag{1}$$

P_D	*Driving Power*	[W]
c_D	*Coefficient of Drag*	[–]
ρ	*Air Density*	[kg m^{-3}]
A	*Vehicle Front Surface*	[m^2]
v	*Velocity*	[m s^{-1}]
c_R	*Rolling Resistance Coefficient*	[–]
m	*Vehicle mass*	[kg]
g	*Gravitational field strength*	[m s^{-2}]
a	*Acceleration*	[m s^{-2}]

Air density ρ is given as 1.25 kg m^{-3} and gravitational field strength g as 9.81 m s^{-2} For deceleration ($a < 0$), P_D might drop below zero and energy is recuperated and fed back into the battery. Recuperation is assumed only for speeds above 5 km h^{-1} [26]. Since the driving data also contain metadata on vehicle size (Section 3.1), vehicle parameters were differentiated by vehicle size and parameters corresponding to the most sold vehicle models per size class in Germany ([27], see Table A1 in the supplementary material). Vehicle efficiency was modeled for each data point of a driving profile based on the component efficiencies of the electric motor, the transmission, power electronics and the battery [28]. Simulating individual driving behavior is a common approach and is also used to estimate BEV suitability (see Introduction). However, the techno-economic comparison of FCI and longer battery ranges requires linking individual driving behavior to FCI needs. Especially the use of individual driving ranges (see Section 2.1.2) and the estimation of charging times for different battery sizes and charging power based on user-specific driving data (see Section 2.2) represents a novel approach in the context of estimating the demand for FCI (see Introduction).

Electric driving was simulated for every driving profile to determine whether this was technically suitable for a BEV. Within the simulation of electric driving, it is assumed that charging with a constant power of 3.7 kW is available every night since overnight charging is considered a prerequisite for driving an EV [29]. Overnight charging is assumed for all parking events longer than 30 min. in the time between 22:00 and 05:00. The charging time comprises the total parking time such that it can begin before 22:00 or end after 05:00. In addition, charging at the company site is assumed if the distance to the company site is less than 500 m.

A reference case was defined to represent today's first generation battery ranges (around 130 km, cf. Section 4.1) and allows only for overnight charging. This means a conventional car would be necessary for long-distance driving. The effect of longer vehicle ranges on BEV potential was analyzed for doubling and tripling this battery capacity. We also analyzed the availability of fast-charging infrastructure. For FCI, 'perfect placement' [20] is assumed, which allows high power fast-charging (up to 150 kW) whenever the vehicle's range is zero. Range buffers due to range anxiety were not considered. Finally, drivers are assumed to accept two fast-charging stops per day (cf. [20]). If a driving profile required more than two fast-charging events per day, it was regarded as not suitable for BEV. For all other profiles, the need for fast-charging was determined individually using the method shown in Section 2.1.2. In addition, we assumed each fast-charging event lasted a maximum of 15 min . The effect of these assumptions on the results is discussed in Section 4.4.

2.1.2. Modeling individual fast-charging demand per year

As the analysis of driving profiles with a limited observation period underestimates long-distance trips and thus the annual need for fast-charging, the number of fast-charging events was estimated based on an approach following Plötz [8] that assumes lognormal distributed daily driving distances. Another alternative is to use the Weibull and Gamma distribution. However, the lognormal distribution has the best goodness-of-fit with German driving data while providing a conservative estimate of annual long-distance trips [30]. The number of yearly fast-charging stops λ^{ZL} for every driving profile results from Eq. (2).

$$\lambda^{ZL} = \frac{\alpha 365}{1+\left(\frac{L}{e^{\mu_L}}\right)^{\frac{\pi}{\eta_L\sqrt{3}}}} + \frac{\alpha 365}{1+\left(\frac{1.8L}{e^{\mu_L}}\right)^{\frac{\pi}{\eta_L\sqrt{3}}}}. \tag{2}$$

α	*Share of driving days*	[–]
L	*Individual vehicle range*	[km]
μ_L	*Average daily driving distance [km] (logarithmized)*	[–]
η_L	*SD of logarithmized daily driving distance [km]*	[–]

The first part of the equation yields the number of days exceeding the vehicle range L, which was determined individually for each vehicle based on individual driving energy demand. The second part of the equation determines the number of days that require two fast-charging stops - it is assumed that the vehicle range$L$ can be increased by a maximum of 80% by the first fast-charging stop, thus resulting in a factor of 1.8. The assumption of a maximum of two fast-charging stops per day is discussed critically in Section 4.4.

2.2. Modeling fast-charging infrastructure demand

The previous modeling step addressed the effectiveness of longer battery ranges and fast-charging infrastructure (FCI) from a user perspective. While the cost of larger battery capacities can be linked directly to the vehicle, the cost of FCI depends on the number of public points needed. The need for FCI has to be deduced from the charging behavior of individuals determined in the previous modeling step. When simulating BEV suitability, the possibility to charge was presumed based on general charging conditions that imply high geographical and temporal availability.

Accordingly, FCI demand is influenced by two criteria. First, FCI has to satisfy a minimum geographical coverage. A heuristic was applied that assumes at least one fast-charging site every 100 km along every German highway in both directions. This would result in 211 fast-charging sites if all the highways in Germany were taken into account. However, 44% of the highways are shorter than 25 km and approximately 8% have an average traffic volume of less than 15,000 vehicles per 24 h, averaged over all BAB sections [28]. For reasons of efficiency, we focus FCI deployment on highways longer than 25 km and with a minimum traffic volume of 15,000 vehicles per 24 h, resulting in 156 fast-charging sites. Only highways were regarded because most of the long-distance trips occur here [13] and 75% of the German population can access a highway within 15 min [31]. Second, each fast-charging site was scaled to satisfy local fast-charging needs such that average waiting times were limited. An average waiting time of five minutes during rush hour was applied and each fast-charging site was scaled individually. If local charging demand exceeded the capacity of a charging site with eight charging points, the construction of an additional charging site was presumed instead of further scaling. This was also to address the need for higher geographical density by adding additional sites. To scale the fast-charging sites, a so-called M/G/s queuing model [32] was used with generally distributed service times, because these are a good match to empirical charging behavior and the commonly used assumption of exponentially distributed service times might overestimate FCI needs [33]. There are no closed analytical solutions for M/G/s systems, so an extension of the Pollaczek-Khinchine formula to M/G/s systems [34] was applied. It uses the coefficient of variation of the underlying charging time distribution C to determine the average charging time of a M/G/s system $W_q^{M/G/s}$ based on the average charging time of the corresponding M/M/s System $W_q^{M/M/s}$ $\left(W_q^{M/G/s} = \frac{C^2+1}{2} * W_q^{M/M/s}\right)$. For the calculation of the average waiting time of an M/M/s, please refer to the literature on queuing models, e.g. [35].

The crucial input parameters for the queuing model are the average arrival rate, mean charging time and distribution of charging times. The arrival rate of BEV λ [#BEV/h] at a fast-charging station was derived from the local demand for fast-charging, which was determined in two steps. First, the number of fast-charging events per year was estimated and distributed among all the fast-charging stations proportionally to the traffic intensity of the respective highway segment. Data from the Federal Highway Research Institute was used for this purpose that contains the average daily traffic volumes (in thousand vehicles per day) for each of the 2570 street-segments of the 13,000 km long German highway network.

For the reference car, the mean charging time μ was derived from real-life fast-charging data retrieved in field projects in the US and Sweden [33]. 50% of battery capacity was the average charging energy per fast-charging session (resulting in an average charging energy of 12 kWh for a medium-sized vehicle). The charging time was determined as a quotient of the charging energy and the assumed effective charging power. However, these real-life fast-charging data refer to today's battery capacities. To estimate the future mean charging energy for longer battery ranges, it was presumed that BEV users align the quantity charged with the additional distance to be covered, i.e. charge the amount of energy needed to reach their final destination. This assumption seems justifiable because fast-charging is probably more expensive than home-charging. Accordingly, the mean charging energy of a fast-charging event was assumed to increase proportionally to the distance to be covered for larger battery capacities. Following the assumption of lognormal distributed driving distances, the recharging needed for the additional distance D_+ was calculated using the mean-excess function of the lognormal distribution [36]. There is a less than proportional increase in D_+ for longer battery ranges. It increases from 56 km for the reference battery capacity by the factor of 1.7 for doubled battery capacities and by the factor of 2.2 for tripled battery capacities. Accordingly, for doubled battery capacities, it is assumed that 40% is recharged on average per fast-charging session (~19 kWh for a medium-sized car); for tripled battery capacities, it is 30% (~22 kWh). We presumed a normal distribution of charging times as discussed above. In this study, a constant fast-charging power of 150 kW was assumed. In addition, FCI with 50 kW was analyzed within a sensitivity analysis.

The advantages of the proposed model to estimate the demand for fast-charging infrastructure (FCI) are its high flexibility and low computation time [37], which make it possible to explore a variety of factors influencing the need for FCI. This approach cannot determine the optimal charging locations, but this was not the aim of this study.

2.3. Cost model

Before describing the cost analysis of this study, it is important to underline that the premise was a BEV is always used if technically suitable (see Section 2.1). The reasoning behind this approach is that the widespread use of BEVs is presumed to be necessary to meet political emission reduction targets and we therefore were interested in the additional cost of driving a BEV compared to a conventional car.

The main output of the cost analysis is the difference in the total Equivalent Annual Cost (EAC) between a BEV and a conventional vehicle (CV), which was calculated for every driving profile i as shown in Eq. (3). The EAC of a good represents a recurring annual payment whose net present value is equal to the net present value of the good over its entire lifetime [38]. The advantage of this metric is that it allows us to compare goods with different lifetimes and costs. In our case, we can compare the cost of bigger battery capacities (to individuals) with the non-individual cost for the deployment and operation of fast-charging infrastructure (FCI). Since the total costs of BEV driving are of interest, the cost of individual driving $EAC_{BEV,i}$ as well as the proportionate EAC of the FCI network EAC_{CI} were included to determine the EAC for a BEV. The EAC of the FCI network was allocated equally to all BEV in the stock $\#BEV$.

$$\Delta EAC_i = \left(EAC_{BEV,i} + \frac{1}{\#BEV} EAC_{CI}\right) - EAC_{CV,i} \tag{3}$$

The conventional car is either a gasoline or a diesel vehicle, depending on which has the lower EAC for the individual user. As shown in Eq. (4), the EAC of individual vehicle use $EAC_{VEH,i}$– for a conventional and a battery electric car – is given as the sum of annualized investments in the vehicle and battery, annual operating costs, annual taxes as well as the annual cost for a rental car (cf. Section 2.1.2). The investments in the battery differ for the different battery ranges and the cost for a rental car only occurs for BEV without fast-charging availability. There are no battery costs or rental costs for a conventional car.

$$EAC_{VEH,i} = \frac{(1+r)^T * r}{(1+r)^T - 1}(I_{Veh} + c_{Batt} * \kappa_{Batt}) + aVKT_i * [c_f * FE_i + c_{O\&M}] + c_{tax} + c_{RC,i} \tag{4}$$

EAC_{VEH}	*Equivalent Annual Cost vehicle*	[€/a]
I_{Veh}	*Vehicle investment (excl. battery)*	[€]
c_{Batt}	*Specific battery cost*	[€/kWh]
κ_{Batt}	*Battery capacity*	[kWh]
$aVKT_i$	*Annual vehicle km travelled*	[km/a]
c_f	*fuel cost (CV); electricity cost (BEV)*	[€/l];[€/kWh]
FE_i_i	*Fuel consumption*	[l/km];[kWh/km]
$c_{O\&M}$	*Cost for operation and maintenance*	[€/km]
c_{tax}	*Annual car tax*	[€/a]
$c_{RC,i}$	*Annual cost for a rental car*	[€/a]
r	*Interest rate*	[–]
T	*Vehicle lifetime*	[a]

The annual operating costs differ for each driving profile due to the individual annual $aVKT_i$ and the individual driving energy demand FE_i as determined in the driving simulation (Section 2.1.1). Individual driving energy demand increases for longer battery ranges due to greater vehicle mass. The economic parameters are summarized in Section 3.2.

The EAC for the FCI network were calculated accordingly (cf. Equation (5)). The first summand represents the annualized investments, the second the yearly operating cost and the subtrahend the yearly contribution margin of the electricity sold at fast-charging infrastructure YCE. Fast-charging operators buy electricity at industrial electricity prices $c_{el,CI}$ due to their high purchase quantities[1] and sell it at a price c_{el} equal to the electricity price for commercial users (c_f in Eq. (4)).

$$EAC_{CI} = \frac{(1+r)^T * r}{(1+r)^T - 1} I_{CI} + \#CP * c_{O\&M,CI} - [(c_{el} - c_{el,CI}) * YCE] \quad (5)$$

EAC_{CI}	Equivalent Annual Cost charging infrastructure	[€/a]
I_{CI}	Charging infrastructure investment	[€]
#CP	Number of fast-charging points	[–]
$c_{O\&M,CI}$	Cost for operation and maintenance	[€/a]
c_{el}	Electricity cost for driving (=c_f in eq 4)	[€/kWh]
$c_{el,CI}$	Electricity price for industrial customers	[€/kWh]
YCE	Yearly charged energy at fast-charging stations	[kwh/a]

Since our focus is on the additional cost of electric driving and not on the profitability of the FCI, the simplifying assumption that commercial BEV drivers pay the same electricity costs for residential and public fast-charging is justifiable. Higher electricity costs at fast-charging stations would lower the EAC of the charging infrastructure by the same amount as it would increase the EAC of BEV driving. Thus, it would have no effect on Eq. (3) and the main results of this paper. However, Section 4.3.2 discusses the profitability of FCI with an electricity sale price of 0.48 €/kWh at fast-charging stations.

3. Data and input parameters

3.1. Driving data

To simulate the real-world energy demand of BEVs, real-world driving data were collected via GPS tracking from 467 conventional commercial vehicles in Germany [39]. The dataset shows mean daily distances of 70 km in line with typical commercial driving distances in Germany (see Fig. 2). The long observation period of 22.5 reported days on average is important for analyzing inter-day variations in driving behavior. The average resolution of three data points per minute allows the modeling of individual driving behavior. However, the relatively low sampling rate might lead to an underestimation of the energy needed for acceleration as discussed in Section 4.4. The characteristics of the driving data are summarized in Table A2 (see supplement).

Additional metadata on car sizes was reported by the companies taking part in the data logging. Car sizes were reported as small, medium, large and light-duty vehicles (LDV) and differentiated by cubic capacity (cf. [23]). The shares of car sizes are shown in Table 2. Mean values are given with plus/minus 1.96 standard errors, representing a 95% confidence band. For comparison, Table 2 also shows the car size shares of newly registered cars to commercial owners in Germany. The share of small vehicles is slightly overrepresented in this dataset, while LDV are overrepresented. This has to be taken into account when interpreting the results.

Finally, it was tested whether the driving behavior represented by our dataset yields usable results. We compared our driving data with the dataset KiD 2010, which is a nationwide representative German survey of driving behavior in the commercial sector with the focus on passenger cars and light-duty vehicles [41]. The observation period of KiD 2010 is one day and the number of vehicles is 49,310 (here, a subset was used since the comparison was limited to commercially-owned passenger cars and light-duty vehicles). As shown in Fig. 2, our dataset is suitable, because it adequately represents driving behavior with regard to the daily distances traveled by vehicles in the German commercial sector.

[1] The distribution of 500,000 electric vehicles with an average annual public fast-charging demand of 100 kWh/a (10 charging events with 10 kWh each) results in an annual fast-charging demand of 50,000 MWh. For two to three charging infrastructure providers, this would correspond to 15,000–25,000 MWh per provider and year.

3.2. Economic parameters

The economic analysis focuses on the additional costs related to longer ranges and the deployment of fast-charging infrastructure rather than on an individual's cost perspective. Therefore, the battery costs of automotive manufacturers are the underlying cost level for longer battery ranges rather than consumer prices. The same holds for charging infrastructure cost.

Specific battery system costs were assumed to be 350 €/kWh and 250 and 100 €/kWh for the medium and long-term analysis, respectively. These assumptions are based on an extensive literature review (Table A3, see supplemental material). It should be emphasized that assuming battery system costs of 100 €/kWh is ambitious even for the long term [42,43].

The investments needed for a fast-charging station with a charging power of 50 kW and one with 150 kW are summarized in Table 3 and based on an in-depth analysis of the different components. Table 3 shows the total investments of a fast-charging station as a function of its size (number of charging points). Grid connection costs may vary for different charging sites. For FCI along highways in south Germany, Gras [44] found that grid connection costs can vary by a factor of two. However, because our aim is not to determine optimal charging sites (see Section 2.2), we only consider grid connection implicitly using a rather conservative estimate of grid connection costs to reflect the potential big differences between charging sites. A sensitivity analysis of FCI investments has a very limited effect on the results [28], so it seems reasonable to neglect grid connection issues, especially since our research focuses on highway corridors and conclusions on the national level. A detailed economic analysis of single charging sites is not feasible within the framework of this study and this has to be taken into account when interpreting the results. The annual costs for operation and maintenance are assumed to be € 3000 per charging point, regardless of station size and charging power [28].

The costs to the individual for electric and for conventional driving represent the current commercial sector conditions in Germany. Electricity for driving (c_f) costs 0.21 €/kWh; fuel costs are 1.28 €/l for gasoline and 1.22 €/l for diesel. The industrial electricity price ($c_{el,CI}$) is 0.13 €/kWh. The vehicles are used for commercial purposes so that all costs are without value added tax [28].

The parameters tax, rental car cost and cost for operating and maintenance vary according to vehicle size. German law sets the annual tax on vehicles, which ranges from € 139 (small vehicle) to € 349 (large vehicle) for petrol cars and from € 65 to € 229 for diesel cars. BEVs are tax-exempt in Germany [23]. The costs for a rental car were based on the costs for station-bound car-sharing; the operating and maintenance costs are higher for a conventional car than for a battery electric one, as reported in [23].

The economic analysis assumed an 11.9-year period of ownership, covering the entire lifetime of the vehicle and the battery. The lifetime of the charging infrastructure was assumed to be 15 years for the charging hardware and 35 years for the grid connection. An interest rate of 5% was assumed for all applications.

4. Results

This paper compared the cost-efficiency of deploying fast-charging infrastructure (FCI) with longer battery ranges with the overriding aim of increasing the number of daily trips possible with a BEV. The results are presented in three steps. First, Section 4.1 shows the driving profiles suitable for BEV based on the simulation. Second, Section 4.2 quantifies the number of fast-charging points necessary for long-distance driving. Third, Section 4.3 shows the main results of the techno-economic analysis in the form of a cost-potential curve.

4.1. Individual driving energy demand and potential BEV usage

Modeling the longitudinal dynamics allowed to quantify the effect of driving behavior on the energy demand for driving and thus, to obtain an individual's electric range. A high variation in energy demand

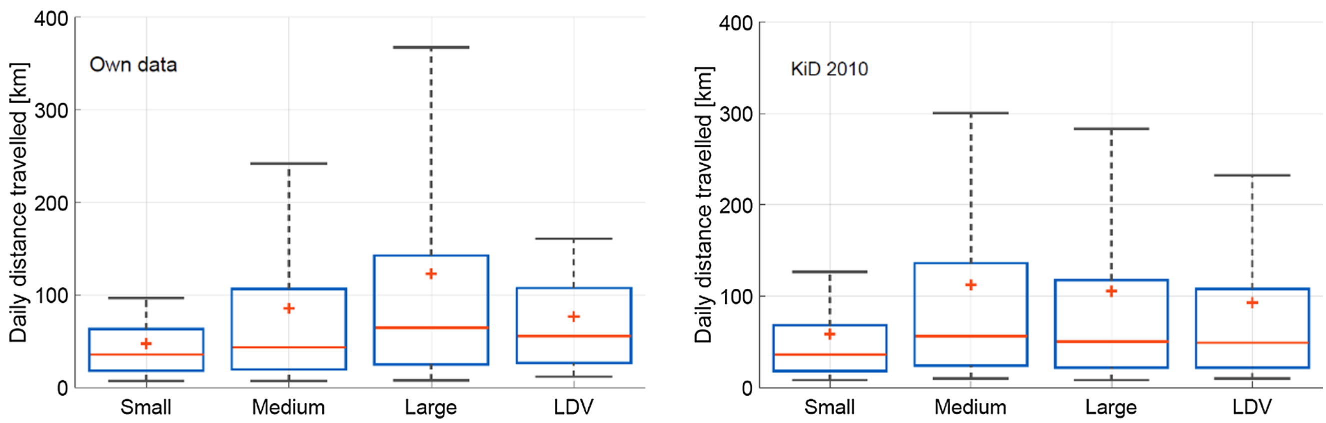

Fig. 2. Daily distances traveled [km] per vehicle size for data used in this study (left) compared with KiD 2010, a nationwide representative survey of commercial driving in Germany (right).

Table 2
Share of car sizes in the driving data.

	Small	Medium	Large	LDV
This dataset	24.4% ± 3.9%	43.9% ± 4.9%	12.2% ± 3.0%	19.5% ± 3.6%
First registration of commercially licensed vehicles in Germany [40]	20.7%	60.3%	12.9%	6.1%

Table 3
Investments in fast-charging stations as a function of size (base year 2017) [€1000 w/o VAT].

	Number of charging points per station							
	1	2	3	4	5	6	7	8
150 kW	120	148.5	227	255.5	374	402.5	481	509.5
50 kW	45	73.5	117	185.5	229	257.5	301	329.5

Table 4
Average individual driving energy demand [kWh/100 km] (medium-sized vehicles).

Individual driving energy demand [kWh/100 km]	1st quartile	Median	2nd quartile	Mean	Standard Deviation
Reference car	14.5	17.4	21.1	18.3	4.2
Doubled battery capacity	15.7	18.3	21.8	19.1	3.9
Tripled battery capacity	16.9	19.5	22.9	20.3	3.8

was found for the different driving profiles, as shown for all medium-sized vehicles (n = 205) in Table 4. Such a variation in driving energy demand was also found in real-world driving profiles of conventional vehicles [45].

The mean and median of the simulated driving energy demand are in line with EPA fuel economy ratings[2] of actual BEV. Given the assumed battery capacities (Table A1, see supplement), individual battery ranges were calculated as the ratio of usable battery capacity and individual driving energy demand (Table 5). Besides the high spread in individual driving range, the negative effect of increasing battery weight on vehicle range is also obvious. Doubling battery capacity leads to a disproportionate increase in the vehicle range by a factor of 1.9; tripling battery capacity increases the range 2.7 times.

For a high share of vehicles, the number of fast-charging stops per year was found to be well below the assumed threshold of a maximum of 48 charging stops. Even with the reference vehicle, 50% of driving profiles (median) needed no more than 27 fast-charging stops. Nevertheless, some driving profiles showed a very high proportion of long-distance trips. For these driving profiles, a BEV is currently not an option, even with tripled battery capacity (see also Fig. 3). Please note that BEV suitability might be higher for private passenger cars, due to their lower annual VKT (in Germany, cf. [23]).

Fig. 3 shows the potential technical share of BEV. This is the share of driving profiles that can make all of their observation day trips with a BEV (cf. Section 2.1) and that do not need more than 48 fast-charging stops per year for long-distance trips. Over 40% of the analyzed commercial driving profiles could be operated technically with a BEV, even with the reference car and no FCI. Such a high technical potential for EV is known from literature, but the studies often consider private cars. Doubling (or tripling) battery capacities could increase this share to 65% (70%) without fast-charging infrastructure. With FCI, the relevant share would be higher by about 12 percentage points for tripled battery size and by about 14 percentage points for the other two battery sizes. Under the assumptions made, a maximum of about 85% of the driving profiles could be operated as BEV.

The average annual vehicle kilometers traveled (aVKT) increase more for larger battery capacities than for the availability of FCI. For the reference car, aVKT can be increased from 10,500 km/a with no

[2] The EPA rating of the 2017 Hyundai Ioniq Electric, the 2016 BMW i3, the 2016 Volkswagen e-Golf, the 2016 Nissan Leaf and the Ford Focus Electric range from 15.5 to 19.9 kWh/100 km (cf. fueleconomy.gov).

Table 5
Average individual vehicle ranges [km] (all vehicles).

Vehicle specification	1st quartile	Median	3rd quartile	Mean	Standard Deviation
Reference car	110	131	150	129	25
Doubled battery capacity	212	248	200	241	42
Tripled battery capacity	301	348	389	342	54

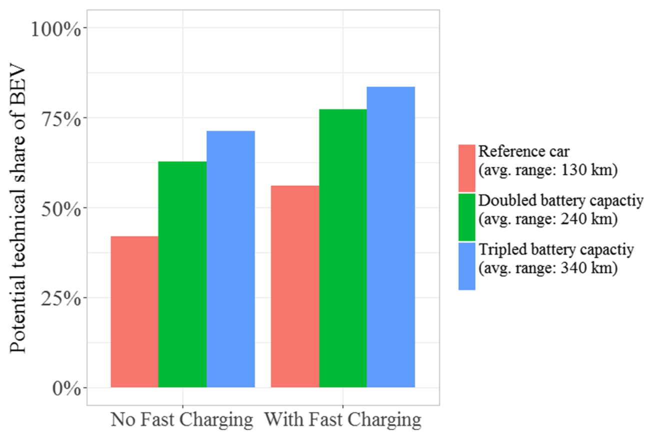

Fig. 3. Share of driving profiles technically suitable for BEV.

fast-charging to 11,500 km/a with fast-charging. The doubling (tripling) of battery capacity increases aVKT to 13,500 (15,000) km/a without FCI and to 15,000 (17,000) km/a with FCI. This result could indicate that FCI is needed especially for infrequent long-distance trips, whereas larger battery capacities allow longer average daily distances on regular driving days.

4.2. Charging infrastructure demand

The results indicate a comparatively low need for FCI. Since widespread geographical coverage of fast-charging is needed, we calculated a minimum number of 211 charging points to cover all German highways and 156 charging sites if short and little frequented highways are excluded (see Section 2.2). This minimum figure is independent of the BEV stock. Demand-driven charging infrastructure increases linearly with the BEV stock ($R^2 > 0.99$). For a charging power of 150 kW and the reference car, ca. 400 fast-charging points are needed for one million BEV and ca. 700 charging points for two million BEV. This results in specific FCI needs of four (P = 150 kW) or seven (P = 50 kW) charging points per 10,000 BEV (see Fig. 4, left). One million BEV (~2.5% of the German car stock) seems to be a critical figure, because the need for specific FCI is higher for a lower BEV stock due to the demand for geographical coverage, but does not decrease much for larger BEV stocks (Fig. 4, left) so that the FCI cost per BEV remains stable.

For longer battery ranges, there is a greater need for FCI: 600 charging points for one million BEV and ca. 1,000 fast-charging points for two million BEV. The need for FCI increases with an increased vehicle range (for our sample), since the possibility to make long-distance trips increases and longer range BEV rely more on FCI. Accordingly, industrial and political decision-makers have to consider more FCI for longer vehicle ranges. While the industry might focus on finding the optimal combination of vehicle range and FCI deployment, policy makers should ensure a suitable use of FCI for BEV with different ranges and thus consider different charging requirements, such as maximum charging power and the resulting charging times.

For FCI deployment, it is sufficient to scale the single charging sites identified for full geographical coverage for a stock of up to two million BEVs. It is only necessary to expand FCI in terms of additional charging sites for larger BEV stocks (Fig. 4, right). Accordingly, the planning of charging sites has to take future needs into account. In particular, grid capacity should allow an expansion of the single charging sites.

To sum up, longer range BEV rely more on FCI for long-distance trips, at least for the commercial vehicle sample used in this study. The demand for charging infrastructure with a lower charging power of 50 kW is higher due to longer charging times (ceteris paribus). About 1400 fast-charging points are needed for one million BEV, and roughly 2500 fast-charging points for two million BEV. Thus, the decrease in the demand for charging infrastructure is not proportional to the increase in charging power.

The calculated ratio of about 4 fast-charging points per 1000 BEV for a stock of 50,000 BEV is well below the findings in other studies (cf. [6,46]) as well as below current fast-charging infrastructure deployment: There are about 30 charging points in Germany per 1000 BEV, about 18 in the US, and about 10 in Norway, [3]. This gap results from our focus on the technically needed FCI for long-distance driving and the comparatively low charging infrastructure density assumed, whereas current charging infrastructure deployment also considers other factors, such as range anxiety. At present, however, the existing charging infrastructure is not used very frequently [33]. This underlines that the current charging infrastructure ratios might decrease in the future once the BEV market takes off. Finally, the finding that only a limited amount of charging infrastructure is needed from a technical point of view is also found in other studies [12,18].

4.3. Determining a cost-efficient system

The results are presented in two steps. First, the investments in longer battery ranges and in the deployment of fast-charging infrastructure are compared that might be especially interesting for political incentives. Second, a cost-potential curve is presented that combines the cost and the technical potential of the different technology combinations. This enables to determine the most cost-efficient option for reaching a certain technical share of BEVs in the fleet.

4.3.1. Investments in fast-charging infrastructure vs. longer battery ranges

First, longer battery ranges and the deployment of FCI are compared based on their investments. Using investments rather than the EAC enables us to draw conclusions that are easier to understand and communicate. In addition, policies are often designed as purchase incentives.

Investments in longer battery ranges are much higher than those in FCI (Fig. 5). Due to the high costs for battery systems, investing in longer ranges adds up to several thousands of euros, even for very low specific battery costs of 100 €/kWh, which are unlikely to materialize in the near term [42]. Investments are shown for an additional range of +100 and +200 km, corresponding to the scenarios of doubled and tripled battery capacities. Investments in FCI are presumed to be equally distributed across all BEVs in the vehicle stock; this results in investments of up to € 500 (€ 200) per BEV for charging infrastructure with 150 kW (50 kW). In the medium term (one million BEV in Germany), the required investments in charging infrastructure may fall below € 50 per BEV. Although fast-charging at lower power rates (50 kW) requires lower investments per charging point (see Table 3), the number of charging points needed decreases with higher charging power so that this is more favourable in the medium term.

As already pointed out, the demand for FCI is comparatively low

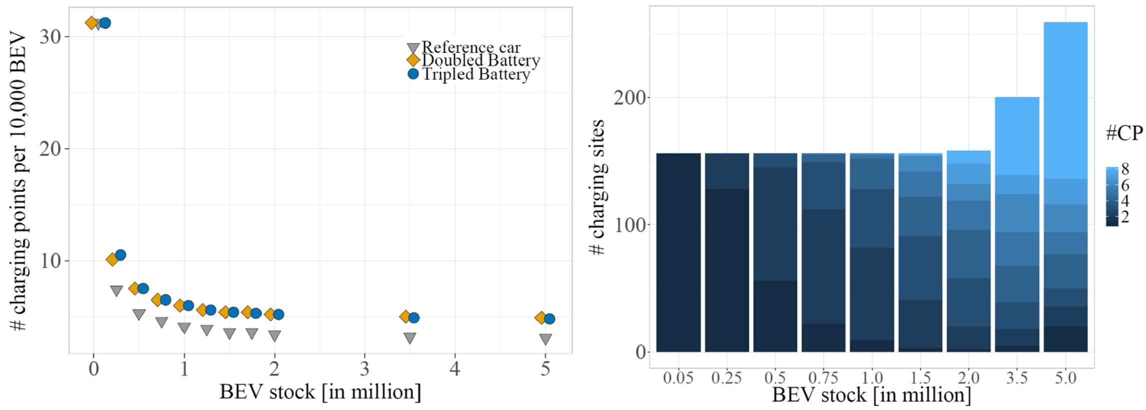

Fig. 4. Calculated fast-charging needs for Germany (P = 150 kW). Left: Number of charging points (#CP) per BEV as a function of BEV stock and battery capacity. BEV stock of doubled and tripled battery capacity is offset by ± 0.045 million for better readability. Right: Number of charging sites by size as a function of BEV stock.

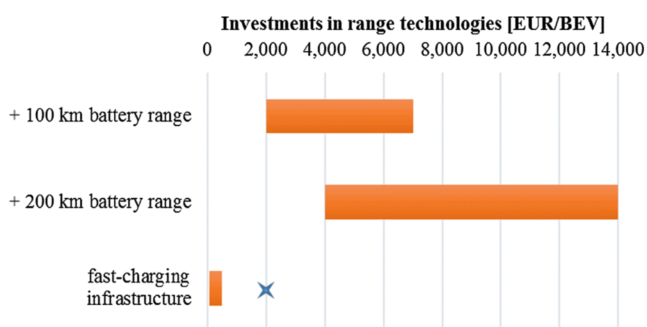

Fig. 5. Bandwidth of investments per BEV for longer battery ranges vs. fast-charging infrastructure. Minimum values only reachable in the long term. The star indicates the investments in fast-charging infrastructure that would result from the current ratio of BEV to fast-charging points in Germany.

which makes them economically favorable. However, even when assuming the German ratio of 30 fast-charging points per 1000 BEV (see Section 4.2), investments in FCI do not exceed € 2000 per BEV for FCI with 50 kW as indicated by the star in Fig. 5. Altogether, the investments in FCI are relatively low compared to the necessary investments in larger battery capacities due to the relatively high battery costs.

4.3.2. A cost potential curve for widespread BEV diffusion

The previous section presented the necessary investments in longer battery ranges and those in FCI. However, the two instruments are heterogeneous in several ways. First, FCI has a much longer lifetime and the potential to generate profits. In addition, as shown in Section 4.1, the two offer different benefits in terms of enabling different fleet shares of BEV.

The question therefore arises as to which combination of battery range and FCI availability is the most cost-efficient with regard to achieving a certain fleet share of BEV. To answer this, we calculated the equivalent annual cost for every driving profile individually and determined the combination of battery range and FCI availability with minimum cost of electrification. Then, for every combination, the average cost for the resulting BEV fleet was determined. The results are given in Fig. 6, which shows the minimum cost for reaching a potential BEV share and the related combinations based on a cost-potential curve. Costs are shown as the average cost difference to a conventional vehicle. A positive value indicates that the use of a BEV comes at a higher cost.

At today's battery costs, electric driving is associated with additional costs of at least € 500 per year for commercial driving (see blue line in Fig. 6). This minimal cost can be realized with the reference car in combination with fast-charging infrastructure, which together allow

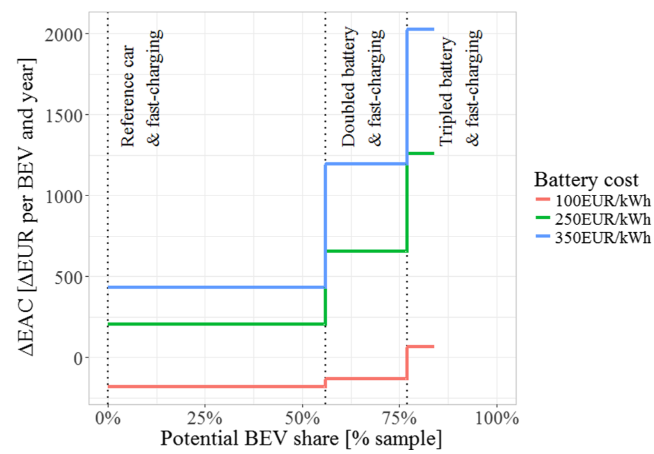

Fig. 6. Cost-potential curve: additional equivalent annual cost of electric driving as a function of the technically feasible fleet share of BEV in the commercial sector.

for ca. 60% of the fleet to be operated as BEV. Cost parity with conventional driving can only be achieved at battery costs of around 100 €/kWh (ceteris paribus, i.e. at today's energy costs etc.), which is highly ambitious. This finding underlines the fact that the current market limitations are not mainly due to technical reasons, but financial and probably psychological ones.

We show average fleet costs instead of the distribution of individual costs, because we are interested in conclusions on a national scale rather than recommendations at the level of individuals. The total costs vary for individual users in any case due to diverging driving behavior. For example, for the reference car and battery cost of 350 €/kWh, the additional annual costs of a BEV vary for all the technically feasible profiles between −1000 and +1000 euros per year. For approx. 80% of these profiles, however, the costs are between € 0 and € 760 per year. This indicates that the mean values shown in Fig. 6 are characteristic for the majority of driving profiles and that conclusions drawn at fleet level are also valid at the level of individual drivers to a large extent.

FCI reduces the costs for long-distance driving, which makes FCI the cost-minimal solution (see Fig. 6) within the context of this study (cf. Section 2.3 for the economic framework). Consequently, fast-charging is always part of a cost-efficient solution for the electrification of commercial driving (Fig. 6). Accordingly, the nationwide deployment of FCI should be politically supported not only to address range anxiety, but also because FCI reduces the overall cost of electric driving in the medium to long term. Despite this, any public funding or subsidies of FCI should be temporary, because FCI may become profitable quite quickly. Analogously, investing in FCI might be an interesting prospect for car manufacturers, even if FCI is unprofitable to start with. Our results indicate that, with an electricity price of 0.48 €/kWh at fast-charging stations, fast-charging infrastructure could already be operated profitably as a whole for a stock of 50,000 BEV. Even though our analyses are based on vehicles with high annual kilometers traveled and thus a high demand for fast-charging, the literature also provides evidence for the high economic potential of FCI for private cars as well (e.g. in [12,18]). To sum up, financial support is necessary to start with to deploy nationwide FCI, but is should be temporary.

As mentioned above, even the reference car in combination with FCI enables a high technical share of BEV of almost 60%. Nevertheless, longer battery ranges are needed to electrify driving profiles with longer daily distances (see also Section 4.1). To achieve a technically feasible share of more than 60% of BEV in the fleet, battery capacities must be doubled. However, in this case, the average additional costs per year increase to ca. € 1200 per BEV (compared to conventional driving). For technically feasible BEV shares above 80%, battery capacities must be tripled, which comes at an average additional cost of more than 2000 €/a. Under the assumptions made, approximately 15% of the commercial driving profiles cannot be operated as BEVs. Accordingly, the widespread diffusion of BEVs requires financial incentives to compensate for the additional costs, especially those for longer battery ranges. However, because very large battery sizes are only necessary for BEV fleet shares above 75%, financial incentives could be limited as a function of battery capacities. In addition, policies should foster advances in battery system manufacturing because ambitiously low battery costs of around 100 €/kWh are necessary to make electric driving affordable for a wide range of drivers.

4.4. Discussion

The design of our model has limitations because the results depend directly on the assumptions, especially on driving and charging behavior. To account for the corresponding uncertainties, the most important assumptions are discussed based on sensitivity analyses.

For fast-charging, most people seem to accept a maximum of two charging events per day and vehicle [20]. However, this is uncertain so the effect of a maximum of four fast-charging events per day was tested. This would lead to a limited additional share of technically feasible BEV of up to three percentage points. Furthermore, it would increase fast-charging demand per year by about 15%, which in turn would lead to an almost proportional increase in FCI. Furthermore, focusing on the demand for fast-charging infrastructure based on techno-economic requirements neglects other potential factors, such as range anxiety, which could result in a greater demand for FCI than estimated here. The effect on the results of assuming a limited time of 15 min. per fast-charging event is comparable to the increase in the number of fast-charging events per day. Another important factor is the fast-charging power. In this study, a constant fast-charging power of 50 kW and 150 kW was assumed, respectively. For even higher charging power, the techno-economic potential of FCI would increase even further. In addition, only fast-charging was studied and overnight charging was assumed to be available for all vehicles. The latter is a valid approximation for most western countries with wide availability of detached, or semi-detached houses and private garages [33]. However, additional public slow-charging infrastructure will be needed in the long run for other users.

When simulating BEV driving, we neglected the energy needed for cabin heating or cooling. An additional load of 1.5 kW would decrease the share of suitable BEV by up to seven percentage points [28]. In addition, the resolution of our dataset is too low to account for detailed acceleration patterns which could overestimate individual driving ranges. Despite these shortcomings, the simulated average energy demands are consistent with EPA fuel economy ratings [28].

Finally, a BEV is presumed to fulfil all the day-to-day driving needs to be considered as an alternative to conventional vehicles in the long term. However, fleet cars or one of the cars in a multicar household could be operated as a BEV with less strict criteria [47]. In a sensitivity analysis, we found that the share of technically suitable BEV could increase by up to 30% if BEVs only had to complete 90% of daily trips.

Battery ranges and fast-charging infrastructure were treated as two options that could be changed directly and independently. We did not address the comfort aspect of having to spend less time for charging with longer-range BEV, but car makers are likely to design longer-range BEV in line with consumer requirements and comfort despite their lower cost-efficiency. Irrespective of this aspect, the main results for overall cost efficiency remain valid.

We did not study privately purchased vehicles here. However, commercial vehicles are characterized by higher annual kilometers traveled and more frequent long-distance trips than private vehicles. Thus, short range BEV are even better suited for use as private cars and any relatively rare long-distance trip could be covered with FCI [48].

Fast-charging and longer battery ranges have different implications for the energy system that have not been analyzed here. A fast-charging station is most likely to be connected to the 10–20 kV grid and could necessitate grid expansion here at points of high demand. Recharging after long-distance trips at home or the workplace would increase the load on the local distribution grid and could necessitate grid investments, too. The grid reinforcement actually required is still under debate but does not have a significant impact on our findings because investments are required in both cases and our focus is on a cost-efficiency comparison at national level. Accordingly, our results are valid on a national scale and the economic analysis of single charging sites is beyond the scope of this study. The interpretation of the results must take this into account.

4.5. Future work

This study presents a novel and initial approach to compare the cost-efficiency of longer battery ranges with fast-charging infrastructure deployment for widespread BEV diffusion. Due to the still limited diffusion of BEVs, especially in Germany, we had to rely on assumptions about BEV driving and charging behavior as discussed above. In future work, the assumption that driving behavior is not adapted to the constraints of BEV driving has to be tested by comparing driving behavior before and after the switch to a BEV. Empirical charging behavior should be analyzed using longitudinal driving data of electric vehicles (cf. [49] for Norway). Alternatively, more empirical data on the distributions of daily driving distances are required. Finally, the amount of energy charged per charging event is an important parameter for determining fast-charging needs. We confirmed the assumption of normally distributed charging times in [33], but future research is needed here. However, future work is needed, especially to better understand the influence of vehicle range and higher charging power on charging needs. Finally, a techno-economic analysis like this study neglects psychological effects. Further studies are needed to evaluate people's willingness to charge and their psychological need for charging infrastructure in a more developed BEV market.

5. Conclusion

To meet ambitious climate mitigation targets, the transport sector has to reduce its emissions of greenhouse gases to almost zero, and the most promising option for passenger cars are currently electric vehicles (EV) powered by renewable energies. Range anxiety is currently one of the biggest barriers to the purchase of EV. There are two main options available to extend the range of BEV: Increased battery capacity or greater availability of fast-charging infrastructure. The quantitative, model-based analyses carried out here on the basis of real-world driving profiles for Germany allow a number of policy-relevant conclusions to be drawn.

Fast-charging infrastructure should be further expanded since it ensures that users of BEV can complete all their trips. FCI increases the suitability of these vehicles which is necessary for high market shares of EV. The specific investments (€/BEV) in the expansion of FCI are three to seven times lower than those for a significant increase in battery capacity assuming the same market share of BEV. The analyses showed that a battery range of approx. 250 km (~50 kWh) is a reasonable size for many drivers. In combination with fast-charging infrastructure, more than 75% of the fleet can then be operated technically as EV. In addition, average annual kilometers of 15,000 km can be reached. Larger battery capacities do not usually pay off, since most users only have to use them very rarely. For the promotion of electric mobility, this means that support should focus on fast-charging infrastructure. As the analyses have shown, there is an initial need for funding because the capital-intensive fast-charging infrastructure is underutilized to start with. Business models without state support only function once a certain market penetration of EV has taken place.

The analyses also showed that the number of fast-charging stations needed for long-distance driving and thus the required level of funding are manageable in case of demand-based expansion. The total investment in the nationwide expansion of fast-charging stations to reach a minimum geographic coverage in Germany is € 40 million, which is relatively low compared to other infrastructure investments. For a high market penetration (more than one million BEV in Germany), we find that a ratio of less than two charging points per 1000 BEV can satisfy demand. This is significantly lower than other studies and than the current situation in Germany (see Section 4.2). This means that any promotion of fast-charging infrastructure should consider these figures.

It should be mentioned here that comfort considerations of users of BEV were not taken into account. More frequent recharging at fast-charging stations may be considered less convenient than having larger battery capacities. However, there is currently a lack of reliable data on this aspect. The analyses were made for Germany and their transferability to other countries is questionable. However, our research provides a combined perspective of increasing battery capacity vs. expanding fast-charging infrastructure. To the authors' best knowledge, this is the first study of its kind and provides insights for policy making and future research.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2018.10.134.

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