33rd Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14 - 17, 2020

Should taxi specific charging infrastructure be opened to the public for higher profitability?

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Summary

Electric taxis are a promising solution to reduce greenhouse gas emissions and other local pollutants. Since taxis are operated predominantly within city centers, the reduction of emissions is very effective. In addition, the local operation of taxis facilitates electrification. In previous work, we show that charging infrastructure used exclusively by taxis might allow high technical electrification potentials. However, its economic operation remains challenging within the next ten years. Here, we analyse whether taxi charging infrastructure might become profitable if opened to the public in times of high public charging demand. Our results for the case study Karlsruhe, Germany, show that blocking periods of the charging stations hardly impair the technical electrification potential of the taxis, but remarkably improve infrastructure profitability. Accordingly, taxi specific charging infrastructure, partly opened to public, is promising.

Keywords: BEV, case-study, city traffic, DC Fast Charging, energy consumption

1 Introduction

Electric vehicles (EV) are a promising solution for decarbonizing the transport sector and reducing local urban pollution [1]. While their potential to electrify car transport for private vehicles is well understood [2], taxis are particularly interesting for electrification. Taxis are operated in areas with high population density within a limited driving radius and their high daily distances make it possible to refinance the high investments of EV compared to conventional vehicles due to lower operating cost. However, the limited range and long charging times may present a greater challenge for taxi journeys [3].

The operation of electric taxis is feasible and can be profitable [4]. However, a good charging infrastructure net is necessary [4]. Often, taxi specific charging infrastructure is postulated [5]. Yet, charging infrastructure needs high investments. In a previous work [6], we find that although electric taxis might be profitable from taxi perspective, taxi specific charging infrastructure can hardly be operated profitably in the near term, if only used by taxis. While in Karlsruhe, under current circumstances, over 25% of taxi kilometres could be electrified profitably for the taxi driver (even without funding), the investment in taxi specific infrastructure could not be refinanced by charging needs of these electric taxis - considering that the charging would otherwise become too expensive. Today, only one charging point could be refinanced, leading to a techno-economic potential of three percent electrifiable km. However, in the future, profitability of electric taxis will increase, mainly due to falling battery prices, which allows for higher techno-economic potentials of electric taxis. In turn, a higher number of taxi charging points could be operated profitably: in 2025, 15 charging sites could be operated profitably, in 2030 charging options at all 20 taxi stands in Karlsruhe could be operated profitably, allowing for electrifying up 60% of the taxi mileage. Altogether, while in medium to long term, profitability of taxi specific charging infrastructure is given, in the short term, it would be highly unprofitable [6].

Thus, in this paper, we analyze whether taxi charging infrastructure can be operated profitably, if opened to public in specific time corridors during private charging peak demand. To this aim, we deduce these peak demand time corridors from simulation data (c.f. Section 2.2). In our simulation of electric taxi driving (for details see [6]), we assume that taxis have to be charged outside these corridors. Second, we analyze the profitability of the charging infrastructure and the role of income generated by private charging. We focus on battery electric vehicles (BEV) and assume, that taxis are charged exclusively at the taxi specific charging infrastructure. In the following, we distinguish charging sites and charging points. We refer to a charging point as a device suited for charging a BEV that only charges one BEV at a time. A charging site can consist of several charging points at the same location, here at various taxi stands.

2 Methodological approach

First, we simulate electric taxi driving and charging based on taxi driving data from conventional taxis (Section 3.1). Compared to previous work [6], we analyse how the feasibility of electric taxis changes, when taxis are not allowed to charge in peak demand periods at public chargers. To determine these periods, we use EV load profiles at public charging stations which were modelled using the ALADIN model (Section 3.2). As a result, we see whether these blocking periods affect technical feasibility of electric taxi driving or whether taxi charging needs can be easily shifted to outside these windows. Second, we have to determine the potential amount of energy charged of private EVs at taxi charging infrastructure to determine additional income. Finally, we determine the number of taxi charging points needed at the different taxi stands as basis for its economic evaluation.

We simulate electric taxi driving by modelling the battery state of charge (SOC) for each data point in the conventional driving data set. For this purpose, a constant specific driving energy demand is used. The SOC decreases proportionally to the distance travelled and its energy demand. Here, we use BEV model specific energy demand, as given by the U.S. Environmental Protection Agency (EPA) test cycle ratings (model year 2018/2019). Electricity consumption ranges from 17.4 kWh/100 km for the VW eGolf to 20.5 kWh/100km for the Tesla Model S P100D. The BEV´s all electric ranges can be interpreted from Fig. 2 (for details see [6]). Conventional diesel taxis have a high fuel consumption, also due to long idle periods with heating needs. In our analysis, we use a diesel fuel consumption of 10 l/100 km which is an empirical value stated in [7].

The electric taxi can be charged during idle times at a taxi stand. If a vehicle is standing at a taxi stand with existing charging infrastructure, we assume that it will be charged if the vehicle is idling for more than five minutes. The entire idling time ΔtI, can be used for charging, minus a processing time of one minute ΔtH [h]. A fast charge with 50 kW charging power is assumed (with constant power over the entire charging time). Accordingly, charging up to a maximum SOC of 80% is possible. For reasons of comfort, we assume that taxi drivers are only willing to charge at a taxi stand if the SOC is below 75%. In this study, loading is only possible outside of the blocking times T.

The battery state of charge after charging $SOC(t+1)$ is thus calculated as:

$$SOC(t+1) = \min\left(SOC_{max}, SOC(t) + (\Delta tI\ -\ \Delta tH)\cdot a \cdot\ P\ \cdot\ K^{-1}\right) \quad (1)$$

With

$$a = \begin{cases} 1, t \notin T \\ 0, t \in T \end{cases}$$

We determine blocking times T as function of public charging peak demand. Charging infrastructure use is blocked for taxi driving, if public charging demand exceeds a ceartin threshold P_T for peak demand. Here, we distinguish two cases.

Case 1: Peak demand, defined as above 50% of maximum charging demand.

Case 2: Peak demand, defined as above 75% of maximum charging demand.

In Fig. 2, blocking times for case 1 are highlighted.

While case 1 allows for higher additional income due to a proportionally higher amount of energy charged by private cars (compared to case 2), it however will have a stronger effect on BEV taxi potential due to the higher duration of blocking times, and thus, the higher necessity to shift taxi charging demand.

Cost of electric taxi driving are compared to conventional driving based on a total cost of ownership analysis. We compare the cost of the five BEV models with conventional vehicles from the same segment. Since the taxi market in Germany is heavily dominated by Mercedes Benz E-class, this is the most important reference car. For conventional vehicles, Mercedes Benz offers a Taxi package that contains all necessary equipment (roof sign, taximeter...) and has a higher than basic equipment. Thus, for electric taxis to be comparable, purchase prices include an additional taxi package plus additional equipment, if applicable. For details, please refer to [6]. A taxi driving profile is presumed to be techno-economically as BEV if it can fulfill all driving needs at lower TCO than the conventional vehicle. Incentives for electric vehicles are not taken into account. The assumed parameters for calculating operating cost are summarized in Table 1.

Table 1: Economic parameters of CI (w/o VAT). [6]

Symbol	Parameter	Value	Unit
p_{el}	Electricity price taxi	0.21	€/kWh
p_p	Electricity price public charging	0.59	€/kWh
p_{fue}	Gasoline price	1.18	€/l
p_{fuel}	Diesel price	1.06	€/l
$p_{O\&M}$	O&M BEV	0.052	€/km
$p_{O\&M}$	O&M PHEV	0.058	€/km
$p_{O\&M}$	O&M Diesel	0.074	€/km
T_{veh}	Calculatory lifetime (vehicle)	10	a
i_{veh}	Interest rate (vehicle)	2.99%	-
p_{tax}	Vehicle tax BEV	0	€/a
p_{tax}	Vehicle tax PHEV	30	€/a
p_{tax}	Vehicle tax Diesel	340	€/a
p_{ET}	Emissions test	53	€/a

The charging infrastructure operator buys electricity at the industrial electricity price. To private BEV users, electricity is sold at the public charging price. Public charging price is according to current tariffs at fast charging stations (e.g. fastend, allego). Taxis pay a lower charging price, but have to pay additional monthly fees (cf. Section 4). The reasoning behind this approach is that the existence of charging infrastructure has an equal benefit to all electric taxis [6]. We determine the monthly fee in such a way that infrastructure does not become lossy. The monthly basic fee per electric taxi ($MF_v, v \in V$) is then given as:

$$MF_v = \frac{1\,[year]}{12\,[months]} * \frac{1}{\sum_{v \in V} 1} * \left[\sum_c \#CP_c * \left(I_{CI} \frac{(1+i_{CI})T_{CI} \cdot i_{CI}}{(1+i_{CI})\,T_{CI} - 1} + Opex_{CI}\right) - (p_{el} - p_{ind}) * \frac{365}{T} \sum_{v \in V, CI=c} kWh_{charged}(v,c)\right] \tag{2}$$

The monthly fee is calculated as the total cost of infrastructure operation minus the contribution margin of selling electricity to the taxis ($kWh_{charged}(v,c)$) at a price of $p_{el} = 0.21\,€/kWh$. The other parameters are given in Table 2. We adjust the amount of energy charged by the factor $\frac{365}{T}$ to represent a yearly operation. The number of charging points needed per taxi stand c (CP_c) was determined heuristically to serve all EVs charging in parallel at any time.

Table 2: Economic parameters of CI (w/o VAT). CI = charging infrastructure. Data source: [8]

Symbol	Parameter	Value	Unit
I_{CI}	Investments in CI (50 kW)	46,500	€/charging point
I_{CI}	Investments in CI (11 kW)	15,000	€/charging point
p_{ind}	Industrial electricity price	0,13	€/kWh
$Opex_{CI}$	Operating cost (2*50 kW)	3,000	€/a
$Opex_{CI}$	Operating cost (2*11 kW)	1,500	€/a
T_{CI}	Calculatory lifetime	15	a
i_{CI}	Interest rate	5%	-

For further details, please refer to [6].

With EV users meeting their public charging demand at taxi infrastructure, this monthly fee can be reduced. To this aim, we first determine the additional charging demand resulting from public charging r_+ as the integral of public charging demand over time $P_p(p)$, minus the chargin demand that remains at public charging stations P_T. Here, we assume that the cost of every taxi charging station might be reduced by additional revenues from public charging demand which implies that for every taxi charging point there is a corresponding public charging point. If all 20 taxi stands were equipped with charging infrastructure, 73 charging points would be necessary, which might be a reasonable number for a city area of 175 km².

$$r_+ = p_p \int_{t \in T} (P_p(t) - P_T)dt \tag{3}$$

Thus, given that the normalized charging demand (Fig. 2) could represent a charging station with four charging sites with 50 kW charging power each, case 1 implies that two public charging points would be necessary, if two additional taxi charging points could be used. Accordingly, case 2 implies a charging site with three charging points and the use of one taxi charging site. Please note that our results depend on this assumption which may be ambitious, however realistic (see also Discussion Section).

The cost of one taxi charging point is then reduced by $r_+ * (p_p - p_{ind})$ for case 1, for case 2, it is half.

3 Data

3.1 Taxi driving data

The case study results from a close cooperation with Taxi-Funkzentrale Karlsruhe, the largest taxi operator in Karlsruhe. In Karlsruhe, 210 taxis are licensed of which 165 are operated by Taxi-Funkzentrale. In this study, we use anonymized booking data from their taxi fleet management system. We use information on start time, end time and distance of each trip as well as the information at which taxi stand the taxi is idling.

In total, the data of 161 taxis could be used (all diesel), representing 77% of the total 2017 taxi fleet in Karlsruhe. The data was recorded during one month in summer 2017 (15. July 2017 to 14. August 2017). During this period, the taxis travelled 739,923 km in total. The collected real driving data were pre-processed. Summary statistics of the dataset can be found in Table 1.

Table 3: Summary statistics of the taxi driving data.

Parameter	MIN	Mean	Median	MAX
No. of data points per vehicle	1,699	46,244	43,866	125,164
No. of observation days	5	30	32	32
No. of driving days	5	26	28	31
Avg. no. of trips per day	2	17.5	16.9	33.6
Avg. daily VKT	21	170	165	395

VKT: vehicle kilometers travelled.

The daily vehicle kilometres driven (VKT) by taxis are to large part less than 250 km. This could lead to a high electrification potential. For most taxis, however, the maximum daily VKT is more than twice the average daily driving distance (see Fig 1). This means that fast charging infrastructure is necessary for electric taxi driving.

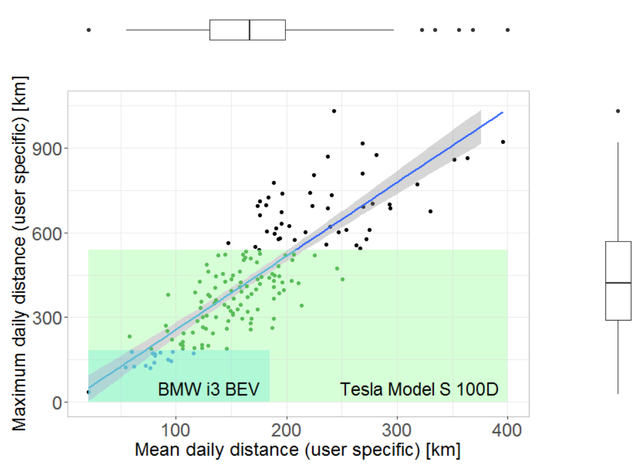

Figure1: Mean vs. maximum daily VKT of the taxi fleet. Blue line indicates a linear fit ($R^2 = 0.68$) with 95% confidence band. Whiskers of boxplots show 1.5 interquartile range. [6]

3.2 EV load profiles at public charging stations

To determine the periods in which taxi charging infrastructure might be opened to the public to absorb peak charging demand at public charging stations, a charging load curve of private EV users charging at public (fast) charging stations within cities is necessary. For such a charging load curve, we use data from the ALADIN model, which is described in detail in [9]. Based on vehicle driving data, vehicle purchase decisions are modelled in ALADIN. For electric vehicles, charging patterns are simulated at home, at work and at public charging stations. The ALADIN model is described in detail in [9].

The resulting load curve of private cars at public charging stations in cities is normalized to a maximum charging power of 200 kW. It shows pronounced daily peaks (Fig. 2). From Monday to Thursday charging demand is highest in the evening and reaches a normalized charging load of 150 kW. On Fridays, the peak charge is highest (up to 200 kW) and the peak demand longest. On Saturdays, the peak load in the early afternoon is below 150 kW without a pronounced peak, while on Sundays the average load is comparatively low, but with a pronounced short peak of almost 150 kW. In Fig. 2, all periods with normalized charging power above 100 kW are highlighted by the grey columns. In these peak demand periods, private EV drivers might use taxi charging infrastructure. Accordingly, we assume that taxis cannot charge in these periods.

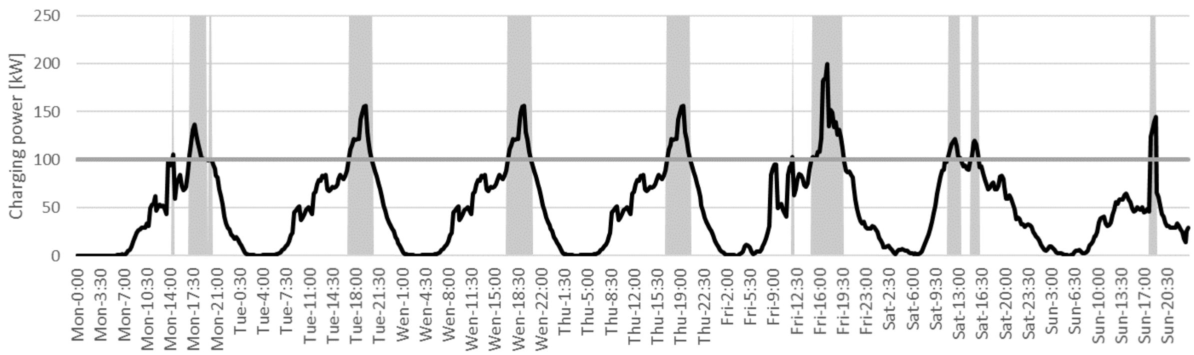

Figure2: Charging load curve in cities (private cars, normalized to 200 kW). Grey columns indicate rush hour peak demand which could be met by taxi charging infrastructure (here 50% of max. demand, case 1). Adapted from [10].

4 Results

There is a conflict of goals between higher additional revenues for taxi charging infrastructure through public charging and less influence on taxi operation. While case 1 allows higher revenues, case 2 has less influence on taxi charging behaviour. In order to illustrate this conflict of goals, we first present the periods in which taxi charging is blocked for public charging. Based on these restrictions, we then show the decreasing electrification potential of taxi driving compared to unrestricted charging. Finally, we calculate the lower cost of taxi operation given the additional revenue from private charging.

Blocking periods

For case 1, for which public charging peak demand is defined as 50% of maximal demand, taxi charging infrastructure would have to be blocked 14% of the time. Blocking periods are mainly in the evening. From Mondays to Thursdays, taxi charging infrastructure would be continuosly blocked from about 17:00 to 20:45 hours. On Fridays, public charging demand happens little earlier, with blocking times lasting from 15:00 to 19:30 hours. On Saturdays, taxi charging infrastructure would have to be blocked from 11:30 to 13:30 and from 15:00 to 16:15. On Sundays, the period would last from 18:00 to 19:00. In these times, public charging demand would yield an additional demand 3000 kWh per week for two taxi charging points.

In contrast, case 2 (above 75% of peak demand) would require taxi charging infrastructure to be blocked only 2% of the time. On Mondays, no blocking would be necessary. From Tuesdays to Thursdays, blocking times last half an hour from 19:15 to 19:45. On Fridays, blocking periods last longer from 16:30 to 18:00. During the weekend no blocking times would be necessary again. This results in an additional public charging demand of 460 kWh per week for one taxi charging point.

Decreasing electrification potential of taxi driving

Blocking taxi charging infrastructure in periods of above 75% public charging peak demand (case 2) has no effect whatsoever on the taxi electrification potential, while blocking periods above 50% of public charging peak demand (case 1) have only a limited effect - the share of electrified kilometers decreases by maximally four percentage points (Fig. 3). In Figure 3, we show electrification potential of all taxis technically feasible as BEV on the left, and all taxis techno-economically feasible as BEV - i.e. with lower total cost of ownership than a diesel taxi, for details cf. [6] - on the right. In addition, we distinguish the case for charging infrastructure being available only at the most frequented taxi stand (CS = 1) and another case with all 20 taxi stands being equipped with charging infrastructure (CS =20).

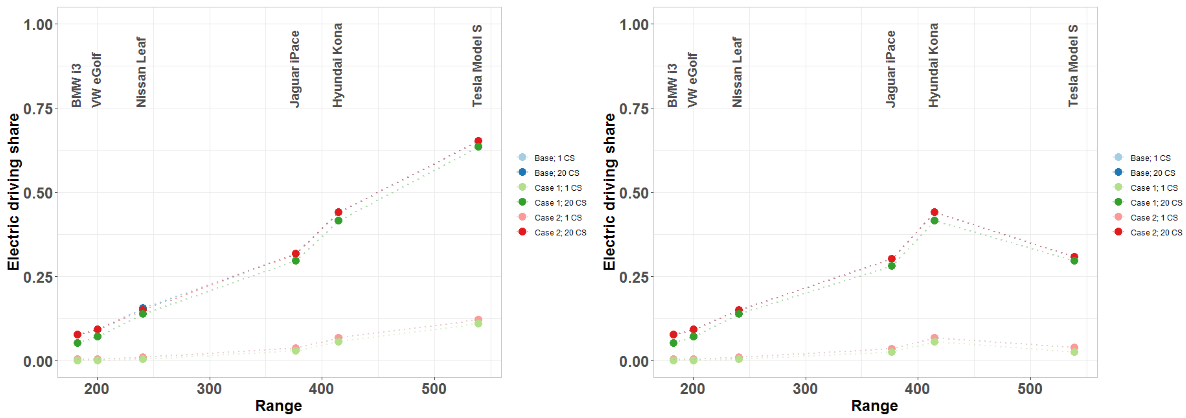

Figure3: Technical (left) and techno-economic (right) potential of electric taxis for different vehicles. Taxi charging infrastructure is blocked in periods of above 50% of maximum public charging demand (case 1) and above 75% peak charging demand (case 2). The results of the base case are identical with case 2. CS1: only one charging site at the most frequented taxi stand is available. CS20: one charging site at all 20 taxi sites.

Reduced taxi operation cost

The higher technical potential of case 2 contrasts with lower revenues compared to case 1. While case 2 could create an additional profit margin of 210 € per week and charging point, this amount increases to 680 € for case 1 (or 1560 € per week and two charging points). Altogether, case 1 allows for lower taxi operation cost, since cost decrease more than technical potential falls, compared to case 2.

As shown in Figure 4, monthly fees necessary per electric taxi to refinance charging infrastructure use might decrease to 65 € (for one charging site) to 270 € (20 sites) for case 2 - compared to 150 € to 450 € per electric taxi and month for the taxi charging infrastructure not being open to the public. For case 1, monthly fees can be omitted for all charging sites. For the case of charging infrastructure. For more details on the base scenario, please refer to [6].

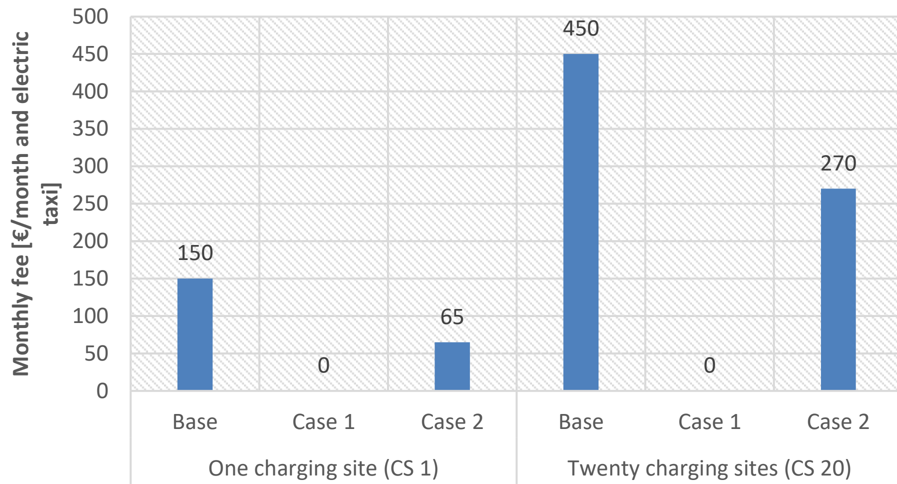

Figure4: Monthly fee that is necessary per electric taxi to refinance its charging infrastructure. Taxi charging infrastructure is blocked in periods of above 50% of maximum public charging demand (case 1) and above 75% peak charging demand (case 2).

Accordingly, while for the base case the vehicle TCO of a BEV taxi must be 1800 € (CS 1) to 5400 € (CS 20) per year lower than a diesel taxi, case 1 decreases the necessary delta TCO to -800 € to -3250 € per year. For comparison: our analysis in [6] shows an average delta TCO of -1200 € for Tesla taxis in Karlsruhe for the year 2020, -2200 € for 2025 and -3500 € for 2030, respectively. Consequently, building up taxi specific charging infrastructure for electric taxis, that is open to the public in peak demand periods, may allow for higher profitability of electric taxi use and thus be a good trade-off between providing taxis a specific charging infrastructure and cost-efficiency.

5 Summary and discussion

Since taxi specific charging infrastructure currently comes at high cost, in this paper, we analyse whether the profitability of taxi charging infrastructure might be increased by additional public charging in peak demand periods. We base our analysis on previous work [6] to which we add the restriction that taxis cannot be charged in these periods. We find that the electrification potential of the analysed fleet of 220 taxis in Karlsruhe, Germany, is hardly affected by the blocking periods under analysis. Accordingly, public charging demand can help to significantly reduce taxi charging infrastructure cost.

For our analysis, we use a charging tariff of 0.59 € per kWh for public charging at taxi infrastructure. This assumption is in line with charging tariffs at fast chargers today. However, these tariffs often refer to fast charging along travel corridors while fast charging within cities might serve as regular charging option for users without a private charging option. Accordingly, willingness to pay for the latter charging option could be lower. For a charging tariff of 0.42 € per kWh charged, we find that for case 1 still five charging sites at taxi stands could be refinanced such that no additional monthly fee for electric taxis would be necessary. Already a charging tariff of 0.48 € per kWh would be sufficient to do so for all 20 taxi stands. For case 2, a charging tariff of 0.48 € per kWh (0.42 €/kWh) would increase the monthly fee for taxis to 90-310 € (100-340 €) per month and electric taxi.

Further, the higher profitability of the taxi charging infrastructure requires a high additional public charging (infrastructure) demand and it could be argued that this demand will emerge at a later stage in the electric vehicle market when the profitability of the taxi charging infrastructure could become uncritical. However, the built-up of public charging is often postulated to allow BEV uptake. Thus, a shared usage of charging infrastructure by taxis and private cars can lower infrastructure cost in the beginning. Since, in the long term, taxi charging infrastructure can be operated profitably only by taxi use, the risk of building charging infrastructure that will be unnecessary in the near future can be reduced or even avoided. In addition, in countries with high home charging availability, such as Germany and the US [11], public fast charging infrastructure within cities will be necessary for BEV users without home charging availability. However, this need will arise in a later market stage, since users without home parking availability are not among the typical early adopters in these countries.

Overall, our results show that shared use of the charging infrastructure by taxis and the public is an interesting case for cost-efficient construction of the charging infrastructure - provided that the infrastructure primarily serves taxis.

Acknowledgments

This publication was written in the framework of the Profilregion Mobilitätssysteme Karlsruhe, which is funded by the Ministry of Economic Affairs, Labour and Housing in Baden-Württemberg and as a national High Performance Center by the Fraunhofer-Gesellschaft.

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