# AN APPROACH TO DETERMINE CHARGING INFRASTRUCTURE FOR ONE MILLION ELECTRIC VEHICLES IN GERMANY

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**ABSTRACT**

Germany has set a goal of having one million electric vehicles in use by 2020. This is a crucial part of the national program *Energy Transition*, which aims to reduced greenhouse gas emissions and transition the economy to renewable energy sources. Achieving this goal requires adequate charging infrastructure, while also remaining economically efficient. Furthermore, infrastructure must be sufficiently robust to accommodate diverse future scenarios. These include variations in the electric vehicle fleet make-up (battery electric vehicles versus plug-in hybrid electric vehicles), range of vehicles, access to charging stations, charging locations, and charging speeds. This paper presents an approach to determine charging infrastructure using the German case study.

We present a demand-oriented methodology to determine charging infrastructure requirements. Utilizing actual travel survey data from a national travel survey, charging demand for user-profiles are determined. Relating charging demand with infrastructure supply (based on the average distance to the next available charging point), we find the required number of charging points. The robustness of the methodology is verified through scenario analyses. The work presents four main findings. First, offering on-street charging in residential areas dramatically increases charging infrastructure. Second, a high percentage of electric vehicles with a private home parking spot notably decreases the total number of charging points. Third, PHEVs slightly increase charging infrastructure demand. Forth, demand for charging infrastructure does not increase linearly with charging demand. Applying the approach to the German case study, between 14,700 and 29,500 charging points are required for one million electric vehicles.

*Keywords*: electric vehicle, charging infrastructure, charging stations, energy, transportation

## INTRODUCTION

In order to mitigate global climate change and reduce urban air pollution, many European countries (*1*), as well as the US (*2*), China (*3*), and Japan (*4*), advocate for electric vehicle (EV) deployment. In Germany, electric vehicles are central to the national program *Energy Transition*, which aims to reduced greenhouse gas emissions and transition the economy to renewable energy sources (*5*). These initiatives generally aim to increase the market share of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). BEVs are powered solely by electricity, whereas PHEVs have an internal combustion engine (ICE) which is combined with a battery that can be charged externally (*6*).

In Germany, the federal government aims to have one million electric vehicles on the roads by 2020 (*7*). While one million electric vehicles represents a market share of only around 2% of the total stock of passenger cars in Germany, selling one million electric vehicles within the next five years signifies a substantial share of new vehicle registrations (*8, 9*). Given that there are three million new vehicle registrations per year in Germany, reaching the goal of one million electric vehicles by 2020 requires that around 7% of all vehicle registrations between now and 2020 are electric vehicles. This high market penetration requires that a large segment of new car buyers, not just early-adopters, opt for electric vehicles (*2*).

The successful mass commercialization of electric vehicles requires sufficient charging infrastructure (*6*). In Germany, no profitable business model for charging stations exists (*10*). Therefore, it is necessary that charging infrastructure is supported by public funds. This raises the question of how much infrastructure is necessary (*11*). The EU also requires that Germany set-up a plan on how to roll out alternative vehicle infrastructure (*11*). Once infrastructure demand is ascertained, necessary public funding and financing schemes can be determined. In this paper we determine the number of charging points required for the German case study. Using this scheme, we identify factors with substantial influence on the number of required charging points.

Based on the premise that electric mobility will be a mass market by 2020, we assume that EVs will be used similarly to today’s relatively new conventional vehicles. Furthermore, potential changes in mobility patterns due EVs is currently unknown. Therefore, we utilize actual travel survey data (i.e., vehicle usage profiles, destination information, parking durations) for conventional vehicles to derive charging demand for electric vehicles, similar to other research (*12*). Our analysis is based on two other critical assumptions. First, we design charging infrastructure such that it allows people to charge in situations during which their cars park anyway (e.g., at work or when shopping). Second, we assume that users do not change their activity and travel patterns due to EVs. Rather, they just choose slightly different destinations.

Given these assumptions, we first derive charging demand and subsequently determine charging infrastructure requirements for one million electric vehicles in Germany by 2020. We exclude charging demand arising from long distance travel on the German National Freeway system (Autobahn) and concentrate on charging demand arising from daily car use. Furthermore, we concentrate on vehicles used by private households.

In the following, we describe our methodology using the case study of Germany. First, we introduce the travel survey data we use; second, we present assumptions for our case study including assumptions that are fixed across different scenarios as well as assumptions that vary across scenarios; third, we lay out the approach to establish charging demand; fourth, we derive charging infrastructure needs from charging demand. In the subsequent section we compare and discuss the results for multiple scenarios. Prior to presenting our methodology, we begin by reviewing the existing literature on charging infrastructure for electric vehicles with a focus on Germany.

## REVIEW

For Germany, the National Platform for Electric Mobility (NPE) recommends the development of 77,100 public charging points for normal and fast charging to fulfill the requirements of one million electric vehicles (*13*). Alternatively, the European Commission suggests 1.5 million charging points in Germany by 2020, of which 150,000 should be publically accessible charging points (*11*). Funke et al. estimate a need for 15,000 charging points for on-street parkers and 2,000 fast charging stations in 2020 based on a user-need analysis model (*14*).

Thus there is substantial variation in the recommended quantity of charging infrastructure due to differences in analysis methodologies. Existing approaches to establish charging infrastructure use complex mathematical models, such as discrete, graph theory based methods (*15*, *16*), or diverse location models (*17*, *18*). These methods primarily serve the goal of guaranteeing a minimum standard of charging services or optimizing the location and timing of charging station deployment.

Currently, detailed data on electric vehicle driving and charging patterns are obtained through EV field studies (*19*-*21*). The challenge with present EV driving behavior is that it represents early-adopters (*2*). It is questionable whether early-adopters reflect future mobility behavior when EVs have become a mass market. As an alternative, Pasaoglu et al. (2013) analyzed whether European national travel surveys could be a potential data source to derive EV usage patterns (*22*). They found that the German National Travel Survey (MiD) is problematic as parking choices for each trip are not given. We address this shortcoming by supplementing the MiD dataset with detailed parking information from the German Vehicle Use Survey (*23*).

Furthermore, Carley et al. (2013) found low interest in electric vehicles among the general public due to the perceived disadvantages of range and charging time (*2*). Consequently, achieving mass commercialization necessitates that electric vehicles allow consumers to maintain their current mobility behavior supporting one of our main assumptions. Thus electric vehicles and charging infrastructure must adapt to users, not vice-versa.

Our approach differs from previous studies in that it derives charging demand in a relatively straightforward manner from existing car usage patterns as observed for conventional cars in the German National Travel Survey. This also addresses perceived disadvantages of EVs by allowing users to keep current mobility patterns.

## DATA

In order to provide an empirical basis for assumptions about charging demand, data from the most recent German National Travel Survey from 2008 (*24*) provide the backbone of our analysis. The MiD data set contains 25,922 households, 60,713 persons, 193,290 trips, and 34,601 vehicles. To match travel behavior of electric vehicles in 2020 as closely as possible, vehicles older than 6 years (about the median age of the German passenger car fleet) were excluded from the analyses. This reduces the sample size of the vehicle data set to 16,419 vehicles.

The MiD survey covers all travel on a given day through 24-hour trip diaries of all members of participating households. These 24-hour person diaries are rearranged into 24-hour vehicle usage profiles representing car use on a typical day in Germany. Both weekday and weekend trips are analyzed. On this typical day, 36% of vehicles have no trips, 28% have one or two trips, and 36% have three or more trips.

## ASSUMPTIONS

The starting point for our study are the assumptions listed in the introduction: EVs are a mass market and utilized like conventional vehicles today, EV users charge at places where they park anyway, and EV users do not change their activity schedule due to electric mobility. In the following we present an additional set of assumptions. Some of these are fixed across different scenarios (overarching assumptions) and others vary such that they define six different scenarios (scenario assumptions).

### Overarching assumptions for all scenarios

Analyzing future use of electric vehicles requires several assumptions regardless of future scenarios, and these are summarized in TABLE 1.

**TABLE 1 Overarching assumptions for all scenarios**

| | Details | EV type | Assumption |
|---|---|---|---|
| Electric range | Average expected electric range for EVs in 2020 | BEV | 150 km |
| | | PHEV | 50 km |
| Maximum distance | Distance of single trip to limit analysis to local travel | BEV / PHEV | 150 km |
| Charge at start of the day | Actual range at the start of the day, if no private parking available at home | BEV / PHEV | 50% of the electric range |
| Distance to next charging point at end of day | Expected distance to reach a charging point the next day, if no private parking available at home | BEV / PHEV | 50 km |
| ICE range extension | Range extension using ICE for PHEVs to reach the next optimal charging point (at home or at work) | PHEV | 25 km |
| Normal charging capacity | Private parking at home | BEV / PHEV | 3.7 kW |
| | Other parking locations | BEV / PHEV | 11.1 kW |
| (Semi-) Fast charging capacity | Trip interruption | BEV / PHEV | 50.0 kW |
| | Other locations | BEV / PHEV | 22.2 kW |
| Range from charging | Charging rate of 3.7 kW | BEV | 19.5 km x h |
| | | PHEV | 19.1 km x h |
| | Charging rate of 11.1 kW | BEV | 48.2 km x h |
| | | PHEV | 47.1 km x h |
| | Charging rate of 22.2 kW[1] | BEV / PHEV | 95.0 km x h |
| | Charging rate of 50.0 kW[1] | BEV / PHEV | 215.0 km x h |
| Minimum time for charging | Normal charging | BEV | 30 min |
| | | PHEV | 30 min |
| | (Semi-) Fast charging | BEV / PHEV | 20 min |

[1] Range from charging limited to 80% of the battery capacity.

In addition to the above assumptions, only BEVs and PHEVs are considered; range extended electric vehicles are omitted due to their statistical insignificance (*25*). We exclude long distance travel even though 24-hour trip diaries also include long distance travel in principle, as they are known to underestimate such relatively rare events (*26*). We also differentiate between charging speeds based on the location of the vehicle (*27*). Parking classifications based on locations are presented in TABLE 2.

**TABLE 2 Parking classifications based on location of EV**

| | On-street | Parking garage | Firm property | Private property |
|---|---|---|---|---|
| **Home** | Public | Private | Private | Private |
| **Work** | Public | Publically accessible | Private | Private |
| **Shopping** | Public | Publically accessible | Publically accessible | Publically accessible |
| **Other** | Public | Publically accessible | Private | Private |

**Scenario assumptions**

There are several factors that potentially influence infrastructure requirements. These factors include fleet composition (i.e., percentage of BEVs and PHEVs), the availability of parking (i.e., charging) at home, and the location of public charging (i.e., on-street). We examine these factors via different alternatives to determine their influence on total infrastructure:

- Fleet composition: In order to determine the influence of fleet composition on infrastructure requirements, two alternatives are evaluated: a BEV dominated EV fleet (2/3 BEVs) and a PHEV dominated EV fleet (2/3 PHEVs).
- Availability of private parking at home: Having a private parking spot at home assumes that the vehicle can be charged overnight at home. The MiD data show that 73% of vehicles have a private parking spot at home (all building types–single family detached houses, multi-family houses, etc.–are considered). The first scenario evaluated is that only those persons with a parking spot at home purchase an electric vehicle (i.e., 100% home parking). The alternative is that electric vehicles are purchased by average consumers; thus, 73% of vehicles have a private parking spot at home. A lower rate is not considered as 96% of currently charge at home (*28*).

- Availability of on-street charging infrastructure in residential neighborhoods: The location of charging infrastructure may play a large role in total infrastructure requirements. In particular, on-street (i.e., curbside) charging infrastructure in residential areas, for those who do not have a private parking spot at home, has a potentially large influence on total infrastructure needs. Therefore, two scenarios are examined: charging infrastructure is not available for on-street locations and charging infrastructure is available at these locations.

The alternatives for these three factors can be combined to a total of eight scenarios. However, the scenario of home parking for 100% of vehicles *and* on-street charging is illogical (there is likely no on-street charging demand if everyone has the possibility to charge at a private parking spot). Thus two scenarios are removed, and six scenarios are examined (see TABLE 3).

**TABLE 3 Scenarios for EV charging infrastructure requirements and the resulting charging points required (distance is to the next available charging point). Charging point numbers are discussed later in the paper. (CI – charging infrastructure)**

| Scenario | Fleet composition | Home parking | On-street CI | Charging points (x $10^3$) ½ km | Charging points (x $10^3$) 1 km |
|---|---|---|---|---|---|
| No. 1 | 2/3 BEV, 1/3 PHEV | 100% | No | 26.5 | 13.3 |
| No. 2 | 1/3 BEV, 2/3 PHEV | 100% | No | 28.6 | 14.7 |
| No. 3 | 2/3 BEV, 1/3 PHEV | 73% | No | 43.2 | 24.7 |
| No. 4 | 1/3 BEV, 2/3 PHEV | 73% | No | 49.8 | 29.5 |
| No. 5 | 2/3 BEV, 1/3 PHEV | 73% | Yes | 136.3 | 94.6 |
| No. 6 | 1/3 BEV, 2/3 PHEV | 73% | Yes | 161.7 | 114.6 |

## DETERMINING CHARGING DEMAND PER VEHICLE

Assuming that each conventional vehicle from our data set is an EV, we now generate a 24-hour charging profile for each vehicle. This charging profile is purely user oriented and consists of individual charging events arising from a) a situational need to charge and b) situational opportunities to charge based on parking duration.

In order to evaluate all the scenarios, we generate four hypothetical situations for each vehicle. These result from combining assumptions about the type of EV-technology and the availability of on-street charging infrastructure:

- *EV-technology:*
    1) Vehicle is a BEV: It has to cover its entire 24-hour mileage purely using battery energy; if single trip distances exceed the vehicle range, the vehicle stops for fast charging.
    2) Vehicle is a PHEV: On average, PHEVs cover two-thirds of their mileage using battery energy; if single trip distances exceed the vehicle range, the vehicle does not stop for fast charging.
- *Availability of on-street charging infrastructure:*
    a) For those who park their vehicles on the street at home or at their job site, there is on-street charging infrastructure available at these locations.
    b) For those who park their vehicles on the street at home or at their job site there is *no* on-street charging infrastructure available at these locations.

Then we place each vehicle into the four hypothetical situations: 1a) through 2b). (The availability of on-street charging infrastructure at home / at the job site does not matter to those vehicles that had the possibility to charge on private property in these locations). We develop an algorithm that generates a corresponding charging profile for each vehicle allowing it to conduct all trips as previously observed under the conditions of the four situations. This charging profile has to fulfill two criteria. First, charging must minimize any disruption to existing travel behavior. Second, the infrastructure must offer the most attractive charging for users. Based on these considerations, we categorized the EV charging into three cases as outlined in the charging algorithm in FIGURE 1.

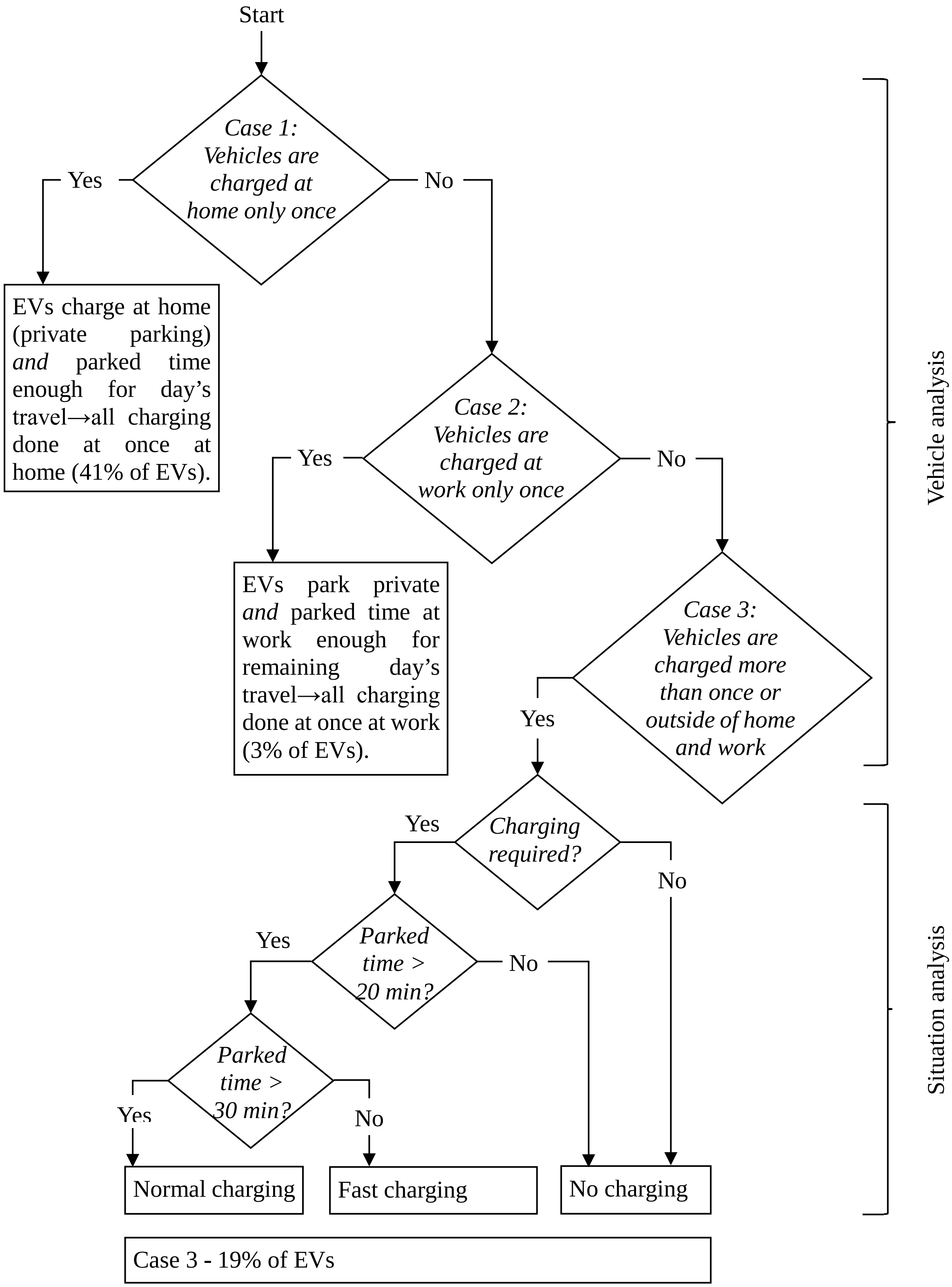


**FIGURE 1 Charging algorithm to determine EV charging profiles. The percentage of EVs for each case are determined for Scenario No. 4 (1/3 BEV, 2/3 PHEV; 73% home parking, no on-street charging). As previously stated, 36% of EVs have no daily trips.**

Applying these charging rules to each vehicle for each of the four situations, 1a) through 2b), generates a detailed, individual charging profile composed of single charging events defined by location/trip purpose, parking classification, charging speed, time of day, and duration. Additionally, considering the attributes of the vehicle (BEV/PHEV, availability of private parking at home) we are now able to compute the number of charging events per vehicle per day, differentiating characteristics of the charging events and vehicle attributes. Average durations per charging event are also computed.

## FACTORING UP CHARGING DEMAND FOR A FLEET OF ONE MILLION EVS

Having determined the charging demand for the 16,419 vehicles in the MiD dataset, we now scale up the results for a fleet of one million electric vehicles. In order to do this, we utilized the distribution of traditional vehicles based on annual mileage from the MiD dataset and use in long distance travel. As long distance travel is not directly included in the MiD, we use a conditional logit estimation to compute a probability of long distance usage. We base the model on data of the 'Mobilitätspanel' (MOP) and the CUMILE model from Institute for Transport Studies (Karlsruhe Institute of Technology).

Given the higher purchase price, the lower operational cost, and the limited range of electric vehicles, we assume that electric vehicles tend to replace conventional vehicles with high annual mileage and infrequent long distance travel. Thus we slightly shift the distribution of the vehicle usage types. We do this by shifting from regular long distance travel (medium and high annual mileage) to no regular long distance travel (medium and high annual mileage). The resulting distribution for electric vehicles is presented in TABLE 4.

**TABLE 4 Distribution of EVs across usage type for the year 2020. Values in parenthesis are the original distribution of vehicles from the MiD dataset. (Low annual mileage is below 10,000 km/yr, medium annual mileage is below 20,000 km/yr)**

| | No regular long distance travel | Regular long distance travel |
|---|---|---|
| **Low annual mileage** | 26% (26%) | 0% (0%) |
| **Medium annual mileage** | 26% (23%) | 13% (16%) |
| **High annual mileage** | 8% (2%) | 27% (34%) |

Next we assign our 16,419 vehicles to the vehicle usage type groups. Then we scale up to a total of one million vehicles in accordance with the distributions to determine the charge demand anticipated by 2020 in Germany. With the scaled up EV fleet of one million vehicles, we compute the following:

- Parking and charging times per parking classification (i.e., private, public, open to public, fast charging),
- Parking and charging times per location (i.e., home, work, shopping, other),
- Number of charges per parking classification (i.e., private, public, open to public, fast charging),
- Number of charges per location (i.e., home, work, shopping, other).

In particular, we compute the total parking time at charging infrastructure that is public or open to the public. This is the summation of the average parking times for each location times the number chargings at each location (only for public locations). FIGURE 2 presents the total parking time and charging time for each charging infrastructure type for all scenarios.

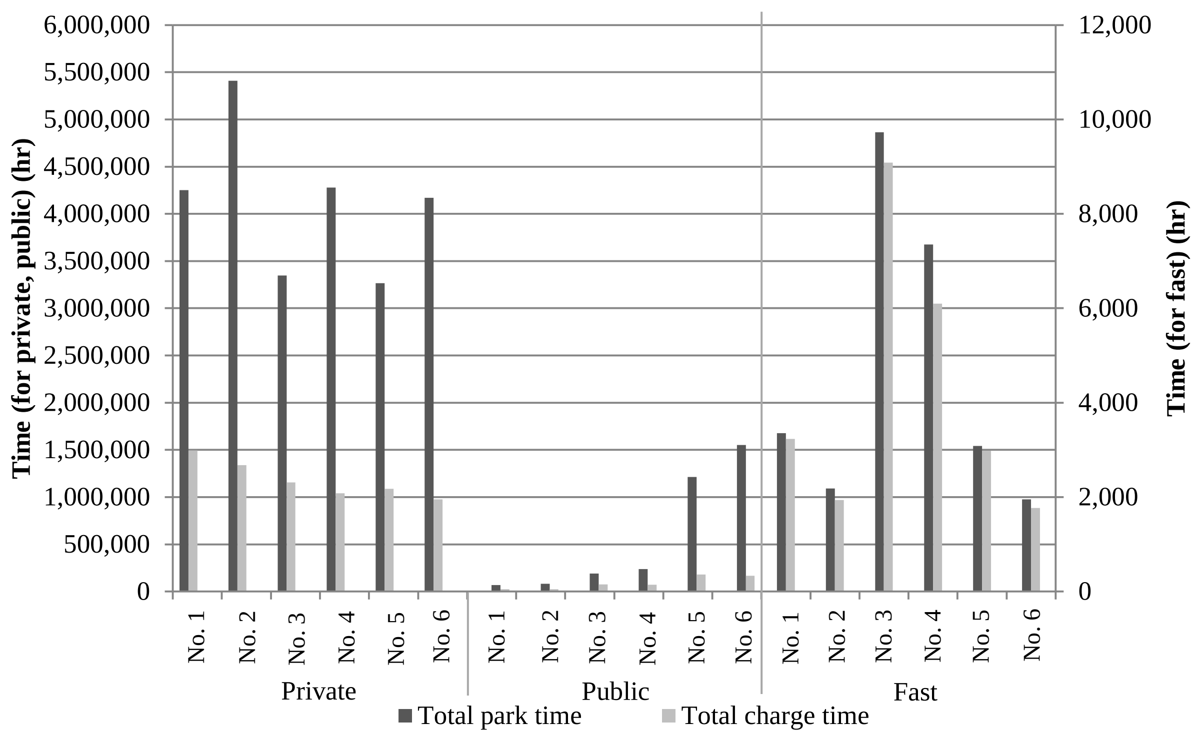


**FIGURE 2 Total parking and charging time per charging type for all scenarios. See TABLE 3 for descriptions of the six scenarios.**

## DETERMINING CHARGING INFRASTRUCTURE FROM CHARGING DEMAND

Having found charging demand, we determine charging infrastructure required for Germany. We focus on charging points that are public or open to the public. While we are able to determine charging demand on a disaggregate level, we discuss the number of charging points as a highly aggregated figure, including all charging options that are public and open to the public (i.e., all trip purposes, normal and fast charging).

### Determining the utilization rate as a function of total charging demand and the number of charging points

As each charging point generates 24 hours of charging infrastructure supply, we relate the utilization rate of the charging infrastructure to total charging demand and the number of charging points based on the fact that:

$$q = \frac{PT}{24 \times CP} \quad (1)$$

where $q$ is the utilization rate of the charging infrastructure, $PT$ is the parking time at charging points until the vehicle is moved [h], and $CP$ the number of charging points.

FIGURE 3 shows how the utilization rate of the charging infrastructure decreases when the number of charging points increases, given a fixed charging demand as expressed by charging hours per day. This raises the question about acceptable levels of utilization in order to determine charging infrastructure demand.

### Finding a quantitative measure for the quality of charging infrastructure supply

For users, high levels of utilization are unattractive if charging points are few and far between. This situation would result in users potentially having to drive long distances to the next station if the first is occupied. On the contrary, a dense and underutilized charging infrastructure is not ideal as this is economically inefficient. We suggest finding a balance between these extremes by combining geographic distance between charging points and utilization rates. We do this by defining an average distance to the next *available* charging point. If this average distance is small, the quality of charging infrastructure supply is high; whereas if the distance is large, the quality of charging infrastructure supply is low. Clustering of charging points is not considered at this point in time. In this study, we evaluate two alternatives: ½ km to the next available charging point and 1 km to the next available charging point.

In order to determine the supply of charging infrastructure, we assume that charging demand is limited to the settlement and transportation area in Germany (13.5% of the total land area of Germany or 48,241 km$^2$). We idealize this area as a square with a length of *L* (220 km) overlaid with a grid street system. Next, we assume that there is a charging point at each grid intersection. In this idealized situation, the average distance to the next available charging point (*DC*) represents the quality of supply of charging infrastructure and can be computed as follows:

$$DC(d,q) = \frac{1}{4}d + qd + q^2 d + q^3 d + \cdots = \sum_{i=0}^{\infty} dq^i - \frac{3}{4}d \qquad (2)$$

where *d* is the average geographic distance between charging points [km].
For a given *DC* and *d* this can be rewritten as:

$$q = 1 - \frac{1}{\frac{DC}{d} + \frac{3}{4}} \qquad (3)$$

where

$$d = \frac{L}{\sqrt{CP}} \qquad (4)$$

and *L* is the length of settlement and transportation area in German [km]. The upward sloping curves in FIGURE 3 show the utilization rate, *q*, as a function of the number of charging points (*CP*) and the average distance to the next available charging point (*DC*) for the two alternatives introduced above (*DC* = 1/2 km; *DC* = 1 km). Given these alternatives as quality criteria for charging infrastructure supply, any point above the respective curve is unsatisfactory for the user (distance to the next charging point is too far), and any point below the respective curve is an inefficient system (the utilization of the charging infrastructure is too low).

**Deriving the number of charging points**

Superimposing the demand and supply curves gives the number of charging points at the intersections. The intersection represents electric vehicle infrastructure that is attractive for users (i.e., the utilization rate of charge points minimizes wait times) and also efficient (i.e., the utilization rate is not so low that points are underutilized).

## RESULTS AND DISCUSSION

The methodology is applied to the case study of Germany for one million electric vehicles with the stated data sets and assumptions. The resulting electric vehicle charging infrastructure demand and supply curves are shown in FIGURE 3.

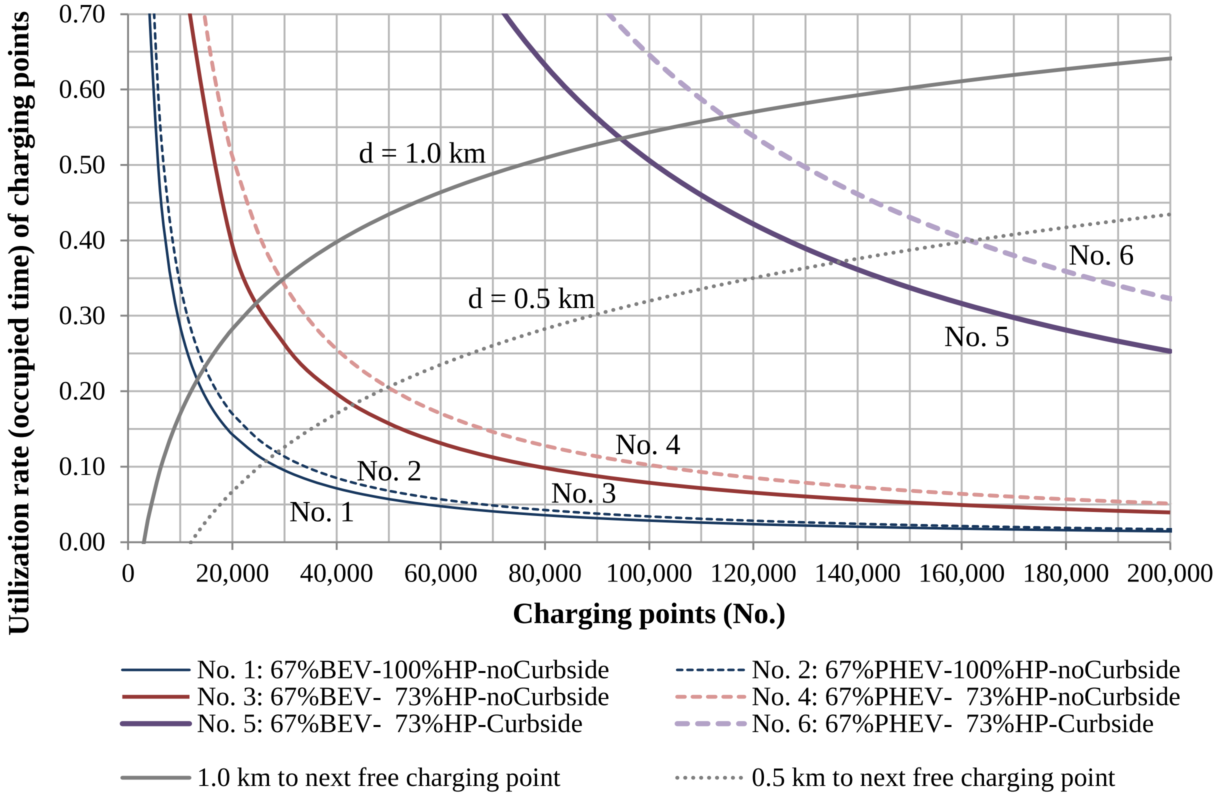


**FIGURE 3 Infrastructure demand curves (downward sloping) superimposed with supply curves (upward sloping). Twelve solutions (i.e., intersections) for charging points are found. (HP – home parking, percentage of vehicles that have a private parking spot at home; Curbside – whether or not vehicles can charge on-street outside residential locations; d – the average geographic distance between charging points). See TABLE 3 for descriptions of the six scenarios.**

The number of charging points is determined by the intersection of the demand and supply curves. The lowest number of charging points (13,300) is for Scenario No 1. (*67%BEV-100%HP-noCurbside*) for a distance of 1.0 km to the next available charging point. The largest number of charging points (161,700) is for Scenario No. 6 (*67%PHEV-73%HP-Curbside*) for a 0.5 km distance to the next available charging point. TABLE 3 summarizes the number of charging points for each scenario.

While the exact number of charging points is of importance, the general lessons from the scenario analysis provide decision-makers with critical insights. There are three factors affecting the demand curves (i.e., fleet composition, home parking, and on-street charging) and one factor affecting the supply curves (i.e., distance to next available charging point). The results show that infrastructure requirements are most influenced by on-street charging followed by home parking and finally fleet composition. Each of these factors will be reviewed in detail.

First, providing on-street charging in residential areas *dramatically* increases required charging infrastructure. Offering on-street charging increases the number of charging points around 3 fold. No other variable results in such a dramatic increase of charging points. The reason for this is that at home (on private parking spots as well on-street spots) cars park much longer than they need to be charged (see FIGURE 2). This results in a charging infrastructure that is blocked much longer than being used efficiently for charging; such infrastructure would be relatively inefficient. Therefore, we recommend not having on-street charging infrastructure in neighborhoods, unless it can be provided at a very low cost.

Second, a high percentage of electric vehicles with a private parking spot at home *notably* decreases the total number of charging stations. The findings show that if only individuals with home parking purchase electric vehicles, charging points decrease between 39 and 51% compared to scenarios with typical home parking availability (i.e., 73% of vehicles have a private parking at home). The aim should not be to limit EVs to users with home parking, but rather to adapt infrastructure to the fact that almost all current users (96%) currently charge at home and that 73% of vehicles have a private parking location.

Third, the results illustrate that a large proportion of PHEVs in the total EV fleet *slightly* increases charging infrastructure. Holding the other variables constant (i.e., home parking, on-street charging) PHEVs require more charging points for all scenarios. This is due to the fact that the PHEVs are modeled to mainly use their electric engine, which have a lower range than BEVs (i.e., PHEV range – 50 km, BEV range 150km). In addition, PHEVs charged faster than BEVs due to their lower range but remain parked at the charging point, which results in an inefficient use of the infrastructure. Having a PHEV dominated fleet increases the required number of charging points between 8 and 18%.

Finally, the influence of the supply side shows that decreasing the distance to the next available charging point *markedly* increases the number of charging points. Logically, having a greater infrastructure supply will result in an increase in the number of charging points. However, this is a non-linear relationship. By halving the distance to the next available charging point, the total number of charging points increases by a factor of 1.4 to 2.0. It is important to note that the methodology focuses on charging *points*. In practice the charging points will likely be clustered at charging stations to minimize infrastructure costs (*14*).

While our methodology is applied to the case study of Germany, it can be used for any location for which suitable travel data is available. The main findings presented above hold regardless of location and provide insights for decision-makers aiming to achieve mass commercialization of electric vehicles.

Based on our analysis, we make the recommendation that Germany needs between 14,700 and 29,500 charging points for a fleet of one million electric vehicles. As on-street charging in residential areas dramatically increases the total charging infrastructure, we recommend a system without on-street charging in residential neighborhoods. We also anticipate PHEVs to dominate the fleet composition in 2020 due to consumer demand. Thus, we recommend planning for Scenario No. 2 or No. 4. Finally, we think that a charging supply with an average distance of 1 km to the next available charging point is satisfactory. This results in 14,700 to 29,500 charging points for Germany in 2020. These values lie well below the recommendations of the NPE (77,100) and significantly below the European Commission (150,000). Our recommendation bounds the value from Funke et al. (approximately 17,000). Our results fall within the general order of magnitude of the other studies. Specific differences stem from the methodologies utilized in each study.

## CONCLUSION

We develop a demand-oriented approach to determine charging infrastructure for electric vehicles. The methodology is based on the criterion that mass commercialization of electric vehicles is dependent on users maintaining their current mobility behavior. Utilizing commonly available travel data, the methodology allows for the calculation of infrastructure demand curves. Critical variables (e.g., parking at home) can be analyzed to inform policy decisions.

We present four key findings from the German case study. First, offering on-street charging in residential areas dramatically increases required charging infrastructure. Second, increasing the percentage of electric vehicles with a private parking spot at home notably decreases the total number of charging stations. Third, PHEVs slightly increase charging infrastructure. Fourth, demand for charging infrastructure does not increase linearly with charging demand.

The proposed methodology has some limitations. First, the methodology is based on daily travel and long distance trips (travel after 150 km) are excluded they are outside the research scope. Second, the analysis only considers BEVs and PHEVs and excludes range extenders. Third, we make the crucial assumption that EV users charge in situations during which their cars park anyway. In this case, normal charging speeds appear to be the natural choice in most situations. This assumption also requires that charging infrastructure is available to the user given minor adaptations of the chosen destination. Such a charging infrastructure set-up is fundamentally different from a set-up that resembles today's refueling pattern at gas stations with a stronger focus on fast-charging infrastructure. However, we believe that our approach can also be adapted to provide quantitative figures for such a gas-station-like charging infrastructure set-up.

Currently we only utilize our approach to derive a highly aggregate figure of the total number of public/publicly accessible charging points irrespective of type (fast, normal) or location of charging point. However, since our methodology to derive charging demand allows for specific figures differentiating location/purpose and type (fast, normal), we believe our approach can also be adapted to quantify demand for charging infrastructure per type.

Future work in the area of charging infrastructure should expand upon user preferences and infrastructure attractiveness. In particular, integrating pricing is a critical topic, which should be explored. Finally, the integration of electric vehicles into the overall electricity network is crucial to achieve system wide energy savings and meet environmental objectives and should be studied further.

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