Public Charging Infrastructure in Germany – A Utilization and Profitability Analysis

Benedict J. Mortimer, Amandus Dominik Bach, Christopher Hecht, Dirk Uwe Sauer, and Rik W. De Doncker

***Abstract*—The current increase in the number of electric vehicles in Germany requires an adequately developed charging infrastructure. Large numbers of public and semi-public charging stations are necessary to ensure sufficient coverage of charging options. In order to make the installation worthwhile for the mostly private operators as well as public ones, a sufficient utilization is decisive. This paper gives an overview of the differences in the utilization across the public charging infrastructure in Germany. To this end, a dataset on the utilization of 21164 public and semi-public charging stations in Germany is evaluated. The installation and operating costs of various charging stations are modeled and economically evaluated in combination with the utilization data. It is shown that in 2019-2020, the average utilization in Germany was rather low, albeit with striking regional differences. We consider future scenarios allowing the regional development forecasting of economic viability. It is demonstrated that a growth in electric mobility of 20%-30% per year leads to a large number of economically feasible charging parks in urban agglomeration areas.**

***Index Terms*—Charging infrastructure, charging station utilization, electromobility, economic analysis.**

I. Introduction

THE electrification of the transport sector plays an important role in meeting Germany's climate target of reducing carbon emissions to 55% of the levels in 1990 by 2030. A breakthrough in electromobility depends not only on the broad range of electric vehicles (EVs) produced but also on the charging infrastructure installed. The public and semi-public charging infrastructure is an important factor for the future. Although it is predicted that in the future, the majority of charging will take place in the private sector, most of the energy will be charged at public charging stations due to the availability of higher charging power [1]. The Federal Government has taken on the task of establishing charging points in Germany by investing around 300 M€ between 2017 and 2020 in the expansion of a publicly accessible charging infrastructure [2]. The dominant charging technology today is conductive charging, where the car is connected to the charging device via a cable. A conductive charging system fulfills the basic task of converting the prevailing alternating current (AC) from the public grid into direct current (DC) adapted to the battery, and thereby galvanically decoupling the vehicle from the grid [3]. This charging technology can be divided into two different variants. The first one is on-board charging while the second one is off-board charging also referred to as DC fast-charging. For onboard charging, the power electronic devices are located inside the EV, which convert and adapt the grid voltage to an appropriate DC voltage to charge the battery. Due to the cost, space, weight, and cooling limitations, the charging power is currently limited. For off-board charging, the necessary power electronic devices are located outside the EV and are directly connected to the DC poles of the battery. Due to less structural limitations, significantly higher charging power levels are feasible [4]. Typically, both charging stations with an AC output of up to 43 kW and fast-charging stations with an output of around 50-150 kW are currently being operated and installed in urban areas. Higher charging capacities (up to 350 kW) are operated and installed at central traffic junctions and along highways in Germany [2], [5]. A broad differentiation of technical grid integration concepts for fast-charging stations can be estimated based on the total installed charging power at a certain location. For an installed capacity of approximately 100 kVA, a separate medium-voltage connection is usually required. Smaller charging points between 50 and 75 can mostly be integrated into the existing infrastructure [6]. It should also be noted that due to the long parking times of vehicles in everyday life, a particularly high charging capacity is only necessary for long-distance journeys [7].

The development status of the public charging infrastructure in Germany differs significantly between cities and regions. Both numbers and types of charging stations and charging park sizes vary [8]. In a few urban regions such as Munich, Hamburg, and Berlin, a large number of charging stations have been installed [9]. In suburban and rural regions, the coverage is currently much lower. Besides the distribution and the power level of charging infrastructure, little is known about the utilization of the charging stations in

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Germany.

The trend of using real-world data to analyze public charging station utilization and charging behavior is fairly new. To this point, there has been little research based on large data with a high number of charging events as well as a large spatial spread of charging stations. Areal-related numbers on the distribution of charging stations in Germany are collected centrally [5], but large-scale data on the utilization of public charging infrastructure in Germany are publicly inaccessible. In [10] and [11], large-scale data are used to characterize the utilization of public charging infrastructure in four cities in the Netherlands. Key performance indicators are introduced that allow a comparison of the charging behaviors in different cities. Also, pattern analysis is performed to indicate the charging station hogging, which is the blocking of charging stations by the users after the charging process is already completed. Reference [12] uses real-world data to perform a statistical analysis on the charging behaviors during different weekdays. The additional energy demand is acquired on a spatial distribution for the Netherlands. In [13], real-world charging data from the city of Berlin is used to show the spatial utilization within the city. It is found that despite an uneven distribution of charging stations, the utilization is relatively equal. It is pointed out that free-floating car-sharing vehicles make out a majority of the charging events in Berlin currently. The problem of charging station hogging is also reported in conjunction with the pricing of the charging processes. The fact that the charging station utilization is far below its capacity is also confirmed by the following analysis. Specifically, addressing fast-charging stations, [14] uses real-world data of fast-charging networks in the US and UK to measure the actual usage and to demonstrate their future importance on main highways. In [15], real-world data are used to investigate the flexibility of charging processes that could help in demand response of the power grid in the Netherlands.

Most economic analyses in literature explicitly address fast-charging infrastructure due to its high investment costs, unclear user's behavior, and low penetration rates of EVs. Reference [16] gives a detailed overview of the cost-structures of fast-charging stations along highways that have been constructed in the UK. Based on the cost and usage data, [16] evaluates the net present value of fast-charging stations under different EV uptake scenarios and concludes that fast-charging stations on main highways are a viable option. In contrast, [17] states that in the year of 2011, fast charging stations in Germany are unlikely to be profitable. However, since 2011, a growth of EVs as well as cost reduction of fast-charging stations has been achieved. Also, [18] concludes that based on different subsidy forms in China, fast-charging stations can achieve good economic results if a certain scale of EVs is reached. Further, a sensitivity analysis shows that the utilization rate as well as the operating expenses (OPEX) are the two most critical factors for fast-charging stations. Economic analyses of today's dominant AC charging infrastructure are hardly covered in the literature. In [19], the economic performance of public charging infrastructure in Europe is examined by a cost-benefit analysis to check for the economic efficiency in several future scenarios. It is concluded that along with the diffusion of EVs first, the AC charging stations within cities will be economically viable followed by the highway fast-charging stations with increasing driving ranges of EVs. Most of the datasets used for analysis are still quite small, which certainly results from the small number of EVs and charging stations so far. Except for the Netherlands, no other examples of a comparable size could be found in literature that allow an analysis of charging infrastructure on a countrywide scale. Especially for Germany, which wants to become a leading pioneer in electromobility, large-scale data are inaccessible. However, in order to evaluate the current development as well as to support the expansion planning, it is necessary to have a good understanding of the utilization and economic efficiency of the charging infrastructure. The latter is of particular interest to evaluate future subsidies for the expansion of charging infrastructure. To help fill this research gap, we use unique data from [20] to show the large-scale utilization of charging stations distributed all over Germany for the first time. Further, we combine the utilization data gathered with a comprehensive cost-benefit analysis of public charging infrastructure to show the economic efficiency on a countrywide scale. Therefore, this paper aims to identify the status of the German public charging infrastructure in terms of utilization and profitability.

Concluding the current state of scientific knowledge, the economical operation of public charging infrastructure depends on a number of factors. The strongest factor, which varies by region, is the number of EVs in conjunction with the number of charging station users. In addition to regional differences in the use of charging stations, there are also differences in the frequency and duration of charging. In addition, the blocking of the charging stations, where the parking times exceed the charging times, is a factor not to be overlooked. Besides usage, the installation costs and grid integration costs play decisive roles, which are usually extremely site-specific.

This paper is divided into the following parts. Section I presents the public charging infrastructure in Germany and the basic charging technologies. In Section II, the data are analyzed and the procedure to determine the utilization and charged energy is presented. In Section III, the charging park model to determine the investment costs is presented. Together with the economic analysis presented in Section IV, Section V shows the results with a discussion.

II. Charging Station Utilization

A. Public Charging Infrastructure in Germany

Figure 1 shows the distribution of all public available charging points according to the German register of charging stations [5]. Currently, 29309 on-board and 2283 off-board charging stations are registered. It can be observed that the 22 charging stations make up the majority of the public charging infrastructure. In the off-board charger segment, the 50 variant dominates, followed by the ultra-fast-chargers on highways. Compared with the AC charging points, the share of fast-charging points, listed in the register, is around 7%. However, it is expected that this number will increase in the future due to the customer's demand and willingness-to-pay for shorter charging times [21]. Especially in urban regions where not every customer has access to a long-term parking spot, providing charging opportunities with 50-75 at places of common interest, such as supermarkets or sport and leisure facilities, is an attractive solution [7]. Out of the 31592 charging points listed in [5], we frequently monitor 21164 charging points in order to generate a representative database for the whole country. The data used for the later analysis are the charging station availability that is accessible via different platforms in Germany. Therefore, the status of each charging point (occupied, empty, or faulty) is monitored and saved every 5 minutes. Additionally, the geographic coordinates along with the charging station power and connector type are saved. Further information and analysis about the data can be found in [20]. The time horizon covered is from May 2019 to April 2020. The data from April 2020 onward is not included due to the unclear influence of the pandemic on the charging behavior. Since the dataset is composed of several sources, duplicate entries cannot be avoided. However, we have tried to remove duplicate charging points as far as possible. Furthermore, not all charging points recorded provide continuous data and charging points with incomplete data are removed from the later analysis.

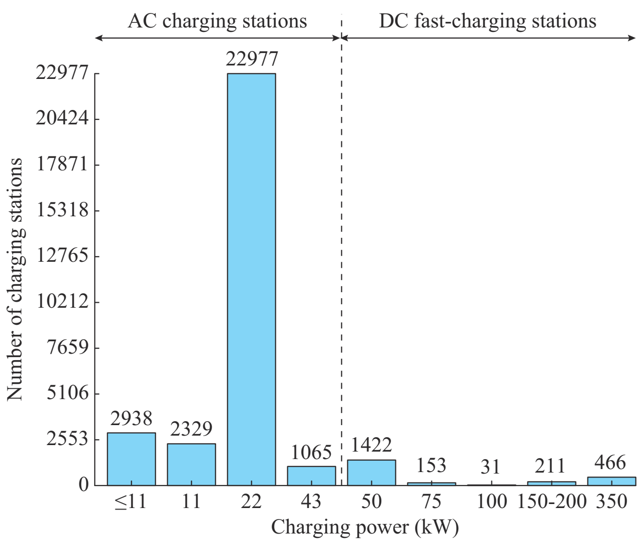


Fig. 1. Distribution of charging stations in Germany by charging power in August 2020.

B. Occupation Time

Based on the data, it is known how long and how often a charging point is occupied by an EV. These events are referred to as occupation events. To get a basic understanding of the duration and frequency of the occupation events and user's behavior, all events in the data set are sorted and divided into AC and DC fast-charging charging points and are shown in Fig. 2. For the AC occupation events in Fig. 2(a), it can be observed that the majority of events are shorter than six hours (blue bars), which indicate a frequent usage. However, 21% of all charging events are longer than six hours (orange bars). Assume that a charging process is completed after a maximum of six hours, a blocking time of 25% of the total occupation time. This is an important metric because it quantifies a frequently-discussed problem that charging stations are occupied for too long by EVs that are already fully charged. Similarly, Fig. 2(b) shows the occupation events at DC fast-charging points. The average occupation time is one hour and is significantly shorter compared with AC charging, as given in Table I. Furthermore, it can be observed that the fast-charging points are only blocked for more than three hours in 2.5% of all cases, which means that during the day or overnight, parking is not an issue. However, if a maximum charging duration of three hours is assumed, the charging points are blocked and unused for 25% of the total occupation time. Nevertheless, it can be concluded that the utilization rate of fast-charging stations is significantly higher due to shorter event duration. Further investigations on the distribution of charging events over time using this data can be found in [20].

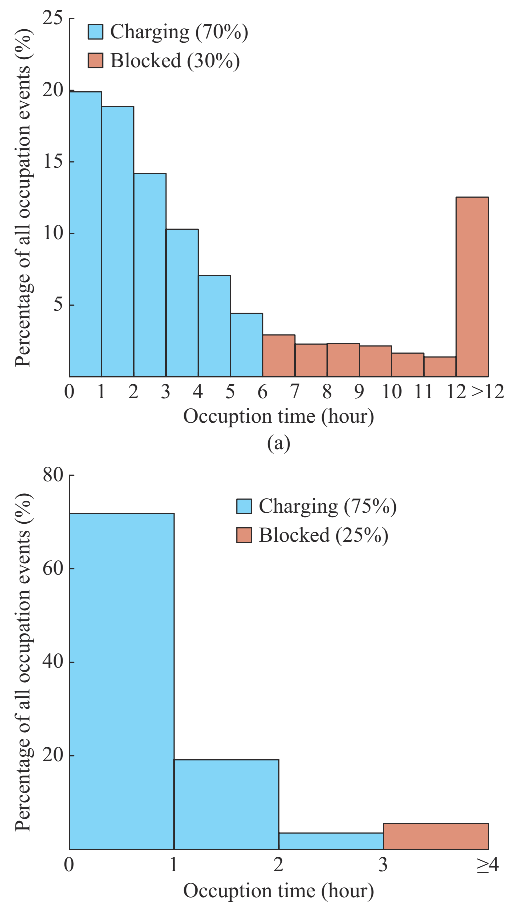


Fig. 2. Distribution of occupation events. (a) AC charging. (b) DC fast-charging.

TABLE I
KEY STATISTICAL DATA FOR AC CHARGING AND DC FAST-CHARGING

Charger type	Charging events	Percentage of events longer than six/three hours (%)	Average occupation time (hour)	Average charging time (hour)
AC	682145	21.0	4.2	3.10
DC	127223	2.5	1.0	0.95

C. Charged Energy

The cumulative usage of a charging point rises linearly with time, which allows representing the occupation of each charging point by using a linear regression over time. Direct conclusions as to whether a charging process is ongoing or has already been completed cannot be drawn directly from this information. Further, the data on the occupation of the charging points cannot be used as a direct measure for the charged energy since it is found unrealistic that a charging process duration is equal to the occupation time, especially for long durations. Therefore, all occupation events are limited to a maximum duration of six hours for AC charging and three hours for DC charging, respectively. Hence, the limited occupation events are considered as the charging event durations and the regression coefficients are calculated and assigned for every charging point, as shown in (1).

$$T_{t,i}^{charged} = \alpha_{0,i} + \alpha_{1,i} T \tag{1}$$

where $T_{t,i}^{charged}$ is the cumulated charging duration that is calulated using the regression; $\alpha_{0,i}$ and $\alpha_{1,i}$ are the regression coefficients; and T is the independent variable in days. Further, this methodology allows predicting the accumulated charging duration for a time horizon of one year since the recorded data do not cover a whole year. In order to estimate the amount of the charged energy, the charging power must be estimated for each charging process. The installed power of the charging points often exceeds the charging power capabilities of the EVs. Therefore, the assumption that each charger operates with its maximum power would lead to an overestimation of the actually charged energy. To get a more realistic value, the EVs sold in Germany until September 2020 are characterized by their available maximum charging power for on-board and off-board charging. Table II contains the number of EVs in Germany and the corresponding maximum charging capacity [22]. Plug-in hybrid electric vehicles (PHEVs) are also considered within the EV quantity that can charge with a maximum power of 3.7 kW. Among the high number of 102175 PHEVs, only 30% are assumed to use the public charging infrastructure. Based on this data, an expected value of the charging power $E(X)$ can be determined for each charger power level. The expected values take into account the number of EVs and their maximum charging power, as shown in Table II.

TABLE II
EXPECTED CHARGING POWER $E(X)$ ACCORDING TO EV CHARGER POWER AND EV QUANTITY IN GERMANY AND MANUFACTURER DATA AT END OF 2019

Charging type	Charger power (kW)	EV quantity	$E(X)$ (kW)
On-board	3.7	102175	3.70
	7.2	24295	5.73
	11.0	59059	7.55
	22.0	57754	10.17
Off-board	40.0	18439	40.00
	50.0	72629	48.45
	100.0	15137	60.12
	150.0	3578	65.42

III. COST MODELS

Every charging station can have one or multiple charging points and is part of one charging park, which can have one or more charging stations with different power levels. Consequently, the charging points are grouped to charging stations and further to charging parks based on the connector type and geographic coordinates. In the following text, the cost models of the components that are necessary to build a charging park are presented. The costs of public charging infrastructure can be divided into capital expenditure (CAPEX) and OPEX shown in Table III. These costs are initially made up of the charger as well as necessary installation costs including the ground work and the supply lines from a grid connection point. In addition to the cable costs, the cabling costs are also taken into account. Besides the capital expenditures, OPEX is considered, which is composed of maintenance, billing and the energy losses of the charger and cables resulting from operation.

TABLE III
COSTS OF PUBLIC CHARGING INFRASTRUCTURE

Cost	Infrastructure
CAPEX	Charger, installation, cables and cabling, grid adaption
OPEX	Maintenance, billing, energy losses
CAPEX (grid adaption)	Transformer upgrade, installation, cables and cabling

The cost composition is very site-specific and depends on the offered charging power as well as the number of charging points installed. Further, if the existing grid infrastructure cannot supply the required power, it has to be extended. The classical way is to upgrade the distribution substations by adding or replacing the grid connection transformer, updating the switch panel, and installing new cables if necessary. The models used to account for these cost factors are presented in the following subsections.

A. Geographic Model

Based on the location, neighboring charging points are grouped to charging parks. Since no comprehensive data on the exact distribution or utilization of low-voltage transformers are available, an even distribution of the transformers will be considered. Therefore, a transformer density of 400 m is assumed, which is based on the data from various grids in German cities and expert interviews with utility operators. The coverage areas of the individual transformers are estimated based on a hexagonal structure, and all charging parks within one hexagon are connected to the transformer in the center, as shown in Fig. 3(a). The distance from each charging park to the next transformer $l_{trafo,dist}$ is determined and used to calculate the grid connection costs.

As a worst-case estimation, the cables as well as the installation costs for the transformers are taken into account.

B. Cables and Cabling

The cabling effort, cable cross sections, and cable length are calculated for each charging park. A unified park model is used that scales with the number of charging points and power levels within a park as depicted in Fig. 3(b). The charging park consists of N charging points with P_{level} rows. The rows represent the number of different power levels within a park, and are placed further away from the point of common coupling (PCC) with decreasing power. All charging points $N_{stations,p}$ of the same power are in one row. The total lengths of all cables in the y- and x-direction for each charging power level with index p are calculated according to (2) and (3), respectively.

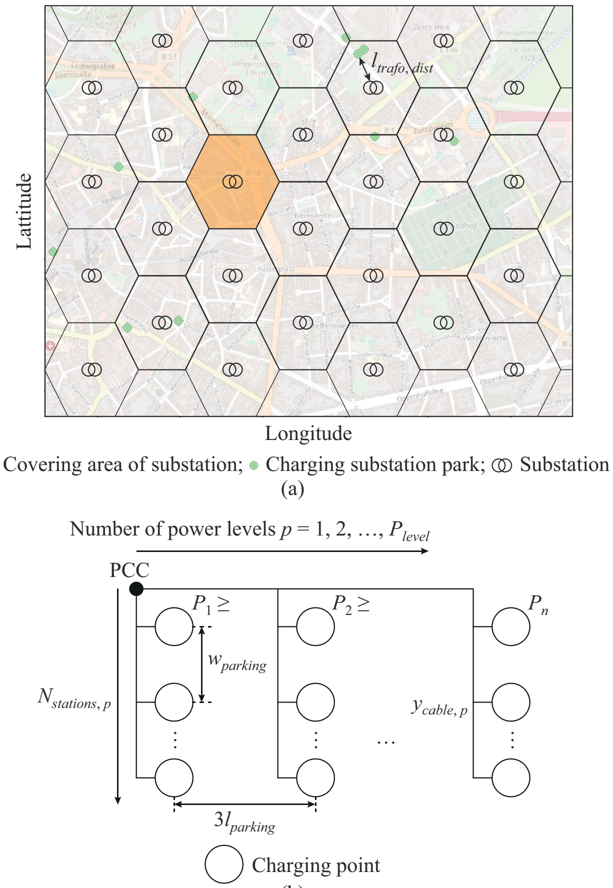


Fig. 3. Geographic model. (a) Transformer distribution model. (b) Charging park model.

$$y_{cable,p} = \frac{N_{stations,p}(N_{stations,p}+1)}{2} w_{parking} \quad p = 1, 2, \ldots, P_{level} \tag{2}$$

$$x_{cable,p} = 3l_{parking} N_{stations,p}(p-1) \quad p = 1, 2, \ldots, P_{level} \tag{3}$$

where $3l_{parking}$ is the distance between rows; and $w_{parking}$ is the distance between each parking spot within one row. The rated current of the charging station I_{rated} is calculated as:

$$I_{rated} = \frac{P_{charger,i}}{\sqrt{3}\, U_{grid} \cos\varphi} \tag{4}$$

where $U_{grid} = 400$ V; $\cos\varphi = 0.9$; and $P_{charger,i}$ is the individual charging station power. On this basis, the cross section of the connection cable is selected according to the standard in [23]. Based on the length and cross section, the cable costs $C_{cable,park}$ are calculated for cables of the type NYY-J using (5).

$$C_{cable,park} = \sum_{p} (y_{cable,p} + x_{cable,p})\, c_{cable,p} \tag{5}$$

where $c_{cable,p}$ is the cost per meter of the cable for the corresponding power level. The cost of the grid connection cable $C_{cable,grid}$ is calculated based on the overall installed charging power, and the distance to the next distribution transformer $l_{trafo,dist}$, which is expressed as:

$$C_{cable,grid} = l_{trafo,dist}\, c_{cable} \sum_{i=1}^{N} P_{charger,i} \tag{6}$$

The costs for cable laying are calculated using a cost rate for cable laying in a defined trench. The cost rate $c_{cabling}$ consists of the working prices for cable laying under asphalt $c_{asphalt}$ and sidewalks $c_{pavement}$ together.

$$c_{cabling} = 0.5c_{asphalt} + 0.5c_{pavement} \tag{7}$$

where $c_{asphalt} = 300$ €/m^2; and $c_{pavement} = 85$ €/m^2. Since the charging infrastructure is usually installed in urban areas, it is assumed that the cables are laid in equal parts under asphalt roads and sidewalks. The distribution is highly site-specific, and therefore only represents an estimate, which should be further differentiated for a detailed analysis. The total length l_{ditch} is calculated according to the park dimensions and the distance to the next transformer substation. The ditch width w_{ditch} is assumed as 0.4 m with an added width of 0.05 m for every cable. The total cabling costs of the park $C_{cabling,park}$ and the grid connection $C_{cabliing,grid}$ are calculated by:

$$C_{cabling,park} = l_{ditch} w_{ditch} c_{cabling} \tag{8}$$

$$C_{cabling,grid} = l_{trafo,dist} w_{ditch} c_{cabling} \tag{9}$$

C. Charging Hardware

On-board charging stations are technically simple and consist of fuses, a ground fault detection unit, a rudimentary communication module, the plug, and a robust housing. In addition, public charging stations are equipped with a display, a communication unit, and a radio frequency identification (RFID) reader for identification and payment. The price range depends strongly on the design and the type of charging station. Wall-boxes are considerably cheaper than charging poles that require an own foundation. The price range is between 500 € and 10000 € [24]. The costs considered for the different charging stations are given in Table IV.

TABLE IV
CHARGER INVESTMENT COSTS

Charger power (kW)	Type	Cost (€)	Efficiency (%)
3	AC	700	100
11	AC	1250	100
22	AC	1250	100
50	DC	15000	94
75	DC	22500	94
150	DC	45000	94

The prices for 11 and 22 charging stations do not differ because only minor extensions are necessary. Off-board charging stations are much more complicated and therefore expensive since they contain the power electronic devices required for charging. A public off-board charging station currently (price level in 2020) costs, in the author's experience, about 500-650 €/kW depending on the configuration. However, in this paper, a price of approximately 300 €/kW is assumed, as predicted in [25]. The costs for AC and DC fast-charging stations are taken from the forecasting results for 2020 [25], which have been verified by commercial offers in the course of this paper.

D. Losses

The conversion losses of the power electronics are only determined and valuated for off-board charging. Since the exact amount of energy supplied is measured at the output of the charging station, according to the German Weights and Measures Act, the conversion losses of AC charging are not taken into account, as these occur in the user's vehicle. The efficiencies assumed for off-board chargers are shown in Table IV. The losses are monetized with an energy purchase price of 0.28 €/kWh.

E. Transformer Costs

As investigated in [6], the installed apparent power of distribution transformers is often the limiting factor for the grid integration of charging stations and usually not the overlaying medium-voltage AC grid. Furthermore, existing low-voltage grids are not capable of carrying the additional current to enable high aggregated charging power ($\geq 100\,\text{kVA}$). Therefore, it is assumed that, for charging parks with an aggregated power greater than 100 kVA, a new distribution transformer is installed. The price of a typical distribution transformer can be calculated according to [26]:

$$C_1 = C_0\left(\frac{S_{1,n}}{S_{0,n}}\right)^x \tag{10}$$

where C_0 is the base cost of a transformer; $S_{0,n}$ is the apparent power rating of the transformer with the cost C_0; and $S_{1,n}$ is the apparent power of the transformer whose cost C_1 is to be determined. Using an exponent x between 0.4 and 0.6, the cost C_1 can be calculated. The transformer costs are calculated using $C_0 = 7900$ €, $S_{0,n} = 100$ kVA, and $x = 0.6$.

F. Total Investment Costs

The total investment costs of each charging park C_{invest} are calculated based on the total costs of all chargers $C_{charger,i}$, the cable costs including ground works and the associated grid connection costs, and a transformer upgrade $C_{transformer}$ if necessary.

$$C_{invest} = \sum_{i}^{N} C_{charger,i} + C_{cable,park} + C_{cabling,park} + C_{cable,grid} + C_{cabling,grid} + C_{transformer} \tag{11}$$

IV. Economic Evaluation

The annuity method based on the dynamic investment calculation is used to evaluate and compare the profitability of the charging parks. The annuity of every charging park is calculated based on the CAPEX, OPEX, and yearly revenue for a period of 8 years. Based on the usage time $T_{t,i}^{charged}$, the expected power P_i^{EX}, and a contribution margin p_i^{margin}, the yearly payment of every charging point i $E_{t,i}$, is calculated by:

$$E_{t,i} = T_{t,i}^{charged} P_i^{EX} p_i^{margin} \tag{12}$$

The margin is assumed to be different for onboard and off-board charging and given in Table V, along with other relevant economic parameters.

TABLE V
Economic Parameters

Property	Value
Interest rate	4%
Time period	8 years
RBF, ANF	6.7 €/year, 0.15 €/year
Price margin AC	0.05 €/kWh
Price margin DC	0.2 €/kWh
Energy losses	0.28 €/kWh
OPEX AC	750 €/year per charger
OPEX DC	1500 €/year per charger

Considering the energy losses, the variable costs $A_{t,i}$ are calculated with the efficiency of the charger η_i and the cost for every p_i^{losses}:

$$A_{t,i} = T_{t,i}^{charged} P_i^{EX} \frac{1-\eta_i}{\eta_i} p_i^{losses} \tag{13}$$

Thus, the annual cash flow for each charging park z_t can be determined by (14), taking into account the fixed costs A_i^{fix}:

$$z_t = \sum_{i=1}^{N}(E_{t,i} - A_{t,i} - A_i^{fix}) \tag{14}$$

Considering constant annual payments and the reciprocal of the annuity factor (RBF), the net present value (NPV) is given by:

$$NPV = \sum_{t=1}^{T}\frac{z_t}{(1-i)^t} = \sum_{t=1}^{T} z_t \cdot RBF \tag{15}$$

Together with the investments costs, the residual value L, and the annuity factor (ANF) for a given interest rate, the annuity a for each charging park is calculated by:

$$a = \left[-C_{invest} + \sum_{t=1}^{T}\frac{z_t}{(1-i)^t} + L(1+i)^{-T}\right]\cdot ANF \tag{16}$$

A. Results

In this subsection, the results are presented based on a regional breakdown for Germany. For this purpose, the charging parks are clustered according to regional areas, and characteristic average values are calculated. Local differences in the usage and characteristics of electromobility in Germany can thus be identified. The average annual charging point utilization is determined and shown at regional areas in Fig. 4.

The regional differences in usage are significant, and the general trend shows less charging activity in rural regions than in urban agglomeration areas. The latter is illustrated by the comparison of population density by region in Fig. 5. The operating hours vary greatly within the individual regions with high values in Berlin, Munich, Stuttgart, and Dusseldorf in the range of 800-1500 hours per year, while the average in Germany is 460 hours per charging point and year. High average utilization rates can be found in regions with large numbers of charging points installed.

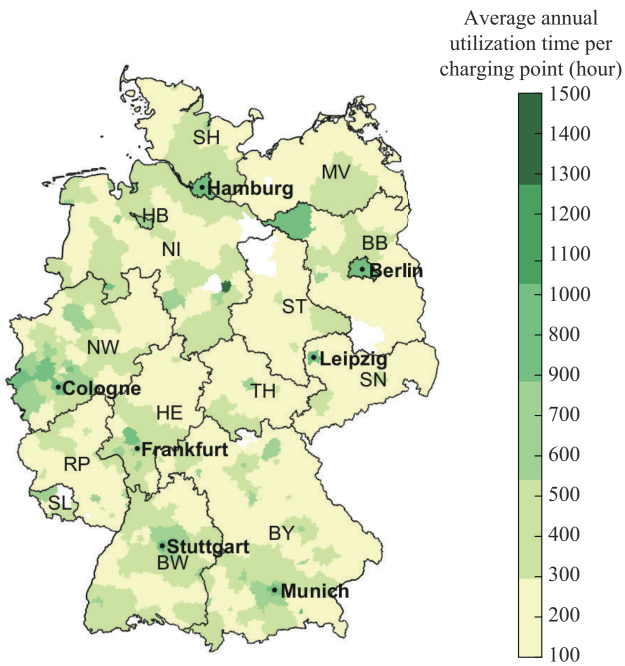


Fig. 4. Average annual utilization hours per charging point and region.

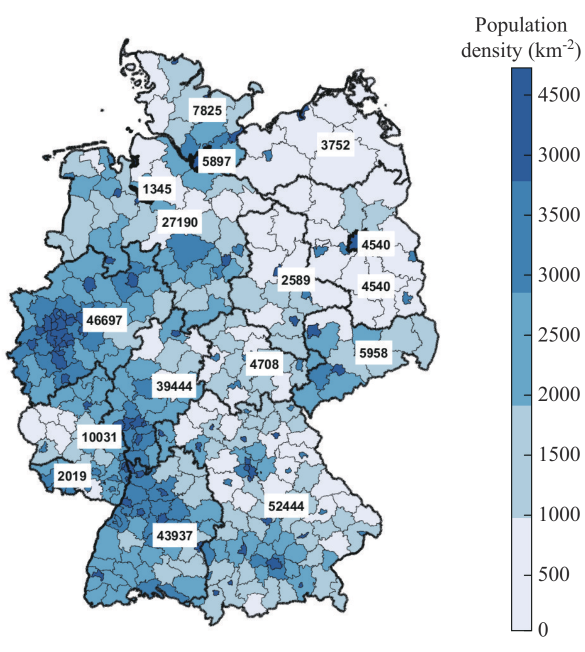


Fig. 5. Population density of Germany and number of registered EVs per state.

Also, the regions with a high utilization and low number of charging points can be identified. Additionally, Table VI shows the number of registered EVs at a state level together with the average annual utilization of the charging points. The variables $a_{\uparrow 20\%}$ and $a_{\uparrow 30\%}$ are the annuity values for scenarios A (20% growth) and B (30% growth), respectively. Surprisingly, very few vehicles are registered in the three states (Hamburg, Berlin, and Bremen) with the highest annual average utilization. One possible explanation could be free-flow car-sharing services operating in these cities, which use EVs registered in other states, as reported in [13] for the city of Berlin. Figure 6 shows the average annual annuities of the charging parks per district areas.

TABLE VI
REGISTERED EVS, UTILIZATION TIME, AND ANNUITIES PER STATE FOR TODAY IN SECENARIOS A AND B

State	EVs	Utilization time (hour)	Annuity (k€)	$a_{\uparrow 20\%}$ (k€)	$a_{\uparrow 30\%}$ (k€)
SH	7825	285	−4.45	−2.70	−1.20
HH	5897	836	−2.14	3.70	7.34
NI	27190	326	−4.36	−2.24	−0.48
HB	1345	626	−3.15	1.31	5.10
NW	46697	429	−3.56	−1.30	0.98
HE	39444	325	−4.43	−2.15	−0.26
RP	10031	251	−5.58	−3.32	−1.41
BW	43937	409	−4.14	−1.41	0.84
BY	52444	409	−3.75	−0.96	1.31
SL	2019	317	−5.76	−3.59	−1.80
BE	8424	694	−1.92	2.60	5.99
BB	4540	233	−4.60	−3.80	−1.75
MV	3752	191	−4.68	−3.18	−1.90
SN	5958	368	−4.11	−2.43	−1.13
ST	2589	227	−5.50	−3.48	−2.14
TH	4708	206	−5.61	−4.35	−3.28

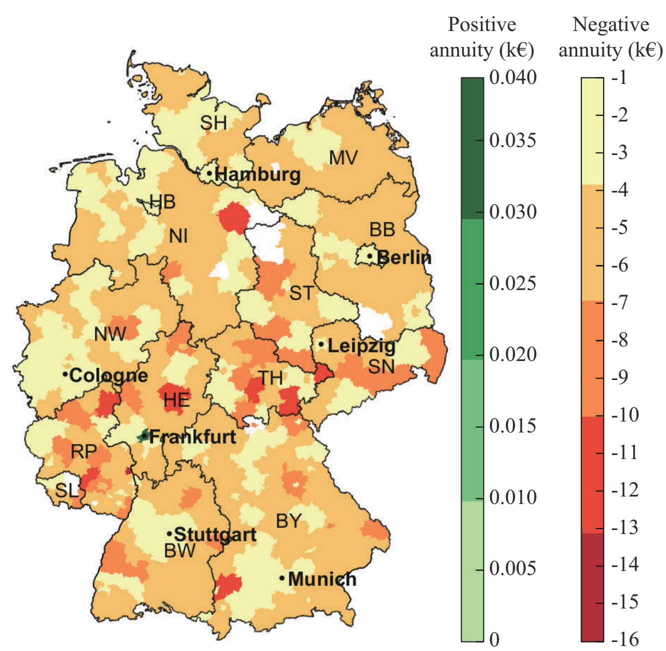


Fig. 6. Average annuity per charging park and region today.

Taking the current utilization rate as a basis, the only region with a positive average annuity is Frankfurt am Main. However, the number of economic feasible charging parks within Germany is 592, which accounts for a total of 1859 charging points. Further, for every charging park, the break-even point (BEP) and the associated yearly utilization is calculated. On average, the BEP is reached for 1560 operating hours per charging point. Assuming a linear relationship between the amount of EVs and the utilization of the charging parks, this value corresponds to a EV-to-charging-point ratio of 15 : 1. Currently, at the end of 2020, this value is around 10 : 1.

The average number of charging sessions per charging point and month is shown for different cities in Fig. 7. Based on the median, it can be observed that the average annuity decreases as the number of weekly events decreases. However, a comparison indicates that the profitability of some regions is currently strongly influenced by the outliers. Few charging parks with high usage can therefore compensate for less economic parks. This is illustrated by the distribution function of annuities over the number of parks in a region, as shown in Fig. 8.

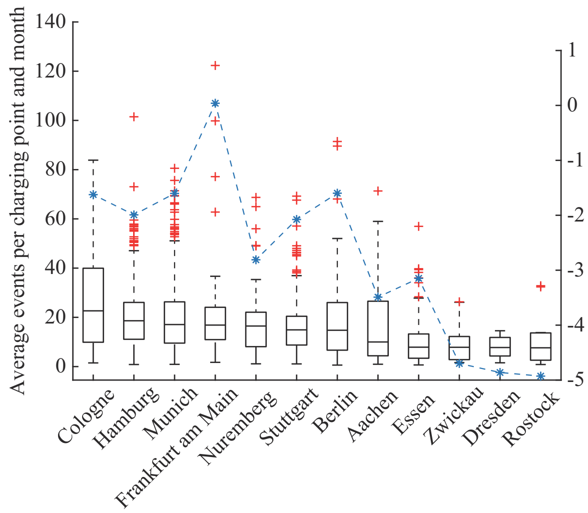


Fig. 7. Average number of charging session per charging point and month for different cities.

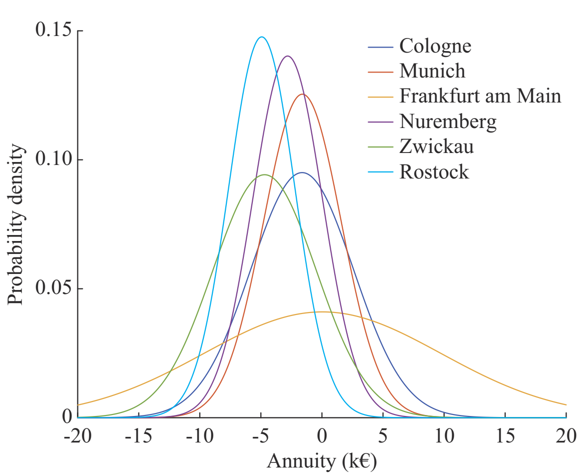


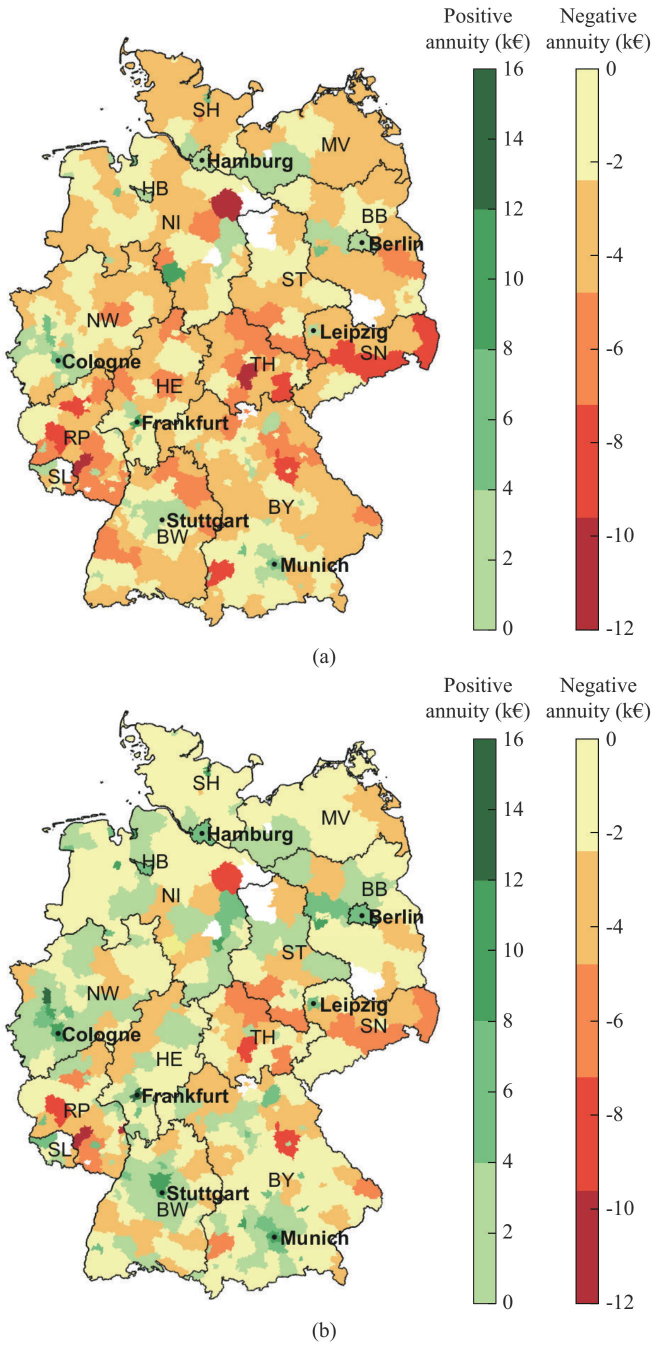
Fig. 8. Distribution of charging park annuities for different cities.

B. Run-up Analysis

In order to make a future-oriented estimate of the economic viability of the charging parks, we consider two ramp-up scenarios. In scenario A, we assume an annual increase in the number of EVs of 20% per year. In scenario B, we assume the annual growth to be 30%. In addition, we assume that the current usage of public charging points is already representative for the future user groups, and that with a linear increase in EVs, the charging events will increase linearly. However, this assumption needs to be reviewed in the future as user's behavior may change when new user groups with different mobility behaviors switch to electric mobility. We also assume in both scenarios that the charging power of the EVs will be equally distributed between 11 and 22 kW. This leads to an annual increase in the expected value of the charging power, which is taken into account accordingly. The number of charging parks is kept constant. The results significantly demonstrate that more regions show positive annuities on average, as shown in Fig. 9. In scenario A, around 35% of all charging parks reach a positive annuity, while in scenario B, almost 48% of all parks are profitable. Comparing the results from Fig. 8(a) and (b), it can be observed that supraregional clusters are formed around the regions with the highest annuities. This indicates that there are a number of pioneering regions in Germany such as Munich, Stuttgart, Frankfurt, Cologne, Hamburg, and Berlin, which also have an effect on the neighboring regions. However, it should be mentioned that the calculation of the run-up scenarios is based on current usage, which is merely scaled. Therefore, the regional addition of charging events in previously weakly used regions due to the increased sales of EVs is not taken into consideration, and this represents a need for further research.

C. Sensitivity Analysis

A total of 8738 charging parks with 21164 charging points in the dataset are identified and evaluated with the proposed method. It has already been shown how the annuity changes positively depend on the increased usage. A sensitivity analysis is performed to show the influence of the assumptions on the overall result. As sensitivities, the costs of charging points, annual operating costs, grid integration costs as well as the profit margins vary by ±20%, and are shown in Fig. 10. A sensitivity of the interest rate is also considered but not shown as it turns out to be minor. Besides a growing number of EVs, the contribution margin is the biggest influencing parameter. In order to achieve an economic operation, the easiest way is to increase the price of the sold electricity. If the profit margin increases, i. e., the ultimate sale price per charged energy in kWh increases, the number of economic parks increases by 57%. Grid integration cost is the second biggest factor. A reduction of 20% leads to an increase in the number of economic parks by 30%. Also, the model uncertainty of the spatial substation distribution is addressed. An increase in the coverage area by 20% leads to a reduction of economic charging parks by 36% as the grid connection costs rise. Further, a 20% reduction leads only to a minor increase of the profitable charging parks. Changes in the operating costs and investment costs of the charging hardware have less impact. Since the ramp-up scenarios in Fig. 9 consider the annual growth rates of 20% and 30% of the operating hours, which are regionally noticeable, the impact for low annual growth rates is considered again here.



(a)

(b)

Fig. 9. Charging stations utilization per region in Germany. (a) Average annuity for an annunal growth rate of 20%. (b) Average annuity for an annunal growth rate of 30%.

It can be observed that the annual growth has the greatest influence on the number of economic parks. An annual increase in the operating time of 10% leads to an increase in the number of economic parks by 150%.

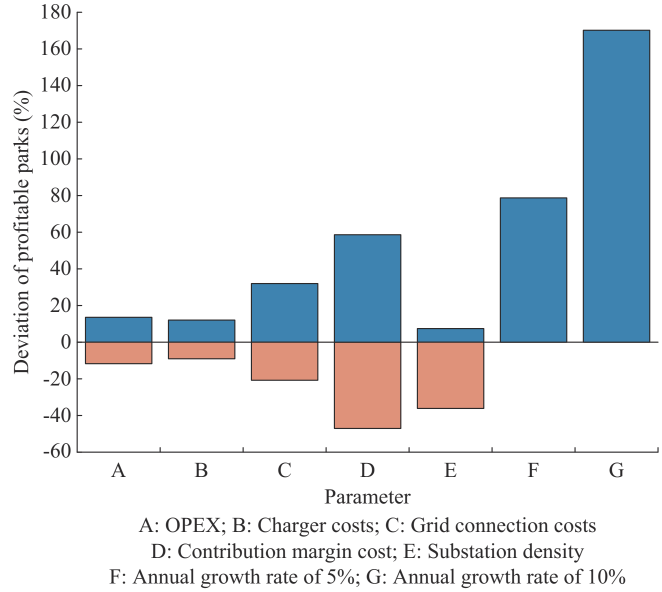


Fig. 10. Impact on number of profitable parks by a ±20% change in assumption.

V. Conclusion

There is limited literature so far about the real-world utilization of public charging infrastructure. Especially for Germany, seeking to become a leading pioneer in electromobility, large datasets are not available. However, in order to evaluate the status, contribute to location planning, and give indications to subsidies, some deep insights of the utilization and economic efficiency of public charging infrastructure are crucial. To address this research gap, we analyze a large dataset of 21164 charging points in Germany and evaluate the economic efficiency based on a comprehensive cost-benefit analysis. It is shown that the overall utilization in Germany is far below its capacity, albeit with striking regional differences. Further, we conduct two EV uptake scenarios, which show the development in economic efficiency of the charging parks in the future. Pioneer areas in Germany are identified, which seem to have an effect on the neighboring areas strongly related to population density. The sensitivity analysis shows that the grid integration costs and the distance to the next grid connection point have a large impact on the economic efficiency. Therefore, the existing electrical infrastructure should be considered when placing future charging stations. In addition, pricing can have a considerable influence. The risk, however, is that users will avoid charging stations that are too expensive.

The successful transition to electromobility in Germany requires an adequate charging infrastructure. The political efforts of the German government in recent years have subsidized the expansion of charging infrastructure in order to solve the chicken-and-egg problem. We have shown that even without subsidies, public charging infrastructure is already a profitable business today in some cases, and will become more attractive as the number of EVs increases. However, it is doubtful that the rapid expansion to date would have been possible without subsidies due to the small number of EVs. While charging infrastructure has a higher utilization in areas with dense population, the question remains as to how rural areas can be economically served in the future.

This paper also comes with some limitations. The data obtained only contain the information on whether a charging point is currently in use or not. The actual amount of energy charged is determined by using the charging point power as well as an average charging power of registered EVs in Germany. The information on the exact charging time is missing, so that no exact statements can be made on the blocking time of the charging stations. By specifying the amount of energy charged per charging session, a much more accurate estimate can be made not only of the economic efficiency, but also of the specific load connected to power grid.

References

[1] A. Windt and O. Arnhold. (2020, Nov.). Ladeinfrastruktur nach 2025/2030: Szenarien für den Markthochlauf. [Online]. Available: https://www. now-gmbh. de/wp-content/uploads/2020/11/StudieLadeinfrastruktur-nach-2025-2.pdf

[2] Nationale Plattform Elektromobilität. (2018, May). Fortschrittsbericht 2018 – Markthochlaufphase. [Online]. Available: http://nationale-plattform-elektromobilitaet. de/fileadmin/userupload/Redaktion/NPEFortschr ittsbericht2018barrierefrei.pdf

[3] *Electric Vehicle Conductive Charging System*, IEC 61851-23: 2014, 2021.

[4] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151-2169, Aug. 2012.

[5] German Federal Network Agency. (2021, Jul.). Charging station map. [Online]. Available: https://www.bundesnetzagentur.de

[6] M. Kurth, M. Gödde, A. Schnettler *et al.* (2017, Oct.). Determination of the integration and influencing potential of rapidcharging systems for electric vehicles in distribution grids. [Online]. Available: https://publications.rwth-aachen.de/record/711961

[7] B. Mortimer, C. Olk, R. G. Kumar *et al.* (2019, Nov.). Fast-charging technologies, topologies and standards 2.0. [Online]. Available: https://www. eonerc. rwth-aachen. de/global/showdocument. asp? id=aaaaaaaaaiwuett&download=1

[8] U. Illmann and J. Kluge, "Public charging infrastructure and the market diffusion of electric vehicles," *Transportation Research Part D: Transport and Environment*, vol. 86, p. 102413, Sept. 2020.

[9] BDEW. (2021, Jun). Ladesäulen: energiewirtschaft baut Ladeinfrastruktur auf. [Online]. Available: https://www.bdew.de/energie/elektromobilitaet-dossier/energiewirtschaft-baut-ladeinfrastruktur-auf/

[10] R. Wolbertus and R. van den Hoed. (2017, Oct.). Charging station hogging: a datadriven analysis. [Online]. Available: https://www.researchgate. net/publication/320245360_Charging_station_hogging_A_datadriven_analysis

[11] R. Wolbertus, R. van den Hoed, and S. Maase, "Benchmarking charging infrastructure utilization," *World Electric Vehicle Journal*, vol. 8, no. 4, pp. 754-771, Dec. 2016.

[12] M. G. Flammini, G. Prettico, A. Julea *et al*., "Statistical characterisation of the real transaction data gathered from electric vehicle charging stations," *Electric Power Systems Research*, vol. 166, pp. 136-150, Jan. 2019.

[13] M. Hardinghaus, M. Löcher, and J. E. Anderson, "Real-world insights on public charging demand and infrastructure use from electric vehicles," *Environmental Research Letters*, vol. 15, no. 10, pp. 1-11, Sept. 2020.

[14] M. Neaimeh, S. D. Salisbury, G. A. Hill *et al*., "Analysing the usage and evidencing the importance of fast chargers for the adoption of battery electric vehicles," *Energy Policy*, vol. 108, pp. 474-486, Sept. 2017.

[15] C. Develder, N. Sadeghianpourhamami, M. Strobbe *et al*., "Quantifying flexibility in EV charging as DR potential: analysis of two real-world data sets," in *Proceedings of IEEE International Conference on Smart Grid Communications*, Sydney, Australia, Nov. 2016, pp. 600-605.

[16] J. Serradilla, J. Wardle, P. Blythe *et al*., "An evidence based approach for investment in rapid-charging infrastructure," *Energy Policy*, vol. 106, pp. 514-524. Jul. 2017.

[17] A. Schroeder and T. Traber, "The economics of fast charging infrastructure for electric vehicles," *Energy Policy*, vol. 43, no. C, pp. 136-144, Apr. 2012.

[18] M. Yang, L. Zhang, and W. Dong, "Economic benefit analysis of charging models based on differential electric vehicle charging infrastructure subsidy policy in China," *Sustainable Cities and Society*, vol. 59, p. 102206, Aug. 2020.

[19] C. Madina, H. Barlag, G. Coppola *et al.*, "Economic assessment of strategies to deploy publicly accessible charging infrastructure," *World Electric Vehicle Journal*, vol. 7, no. 4, pp. 659-669, Dec. 2015.

[20] C. Hecht, S. Das, C. Bussar *et al.*, "Representative, empirical, real-world charging station usage characteristics and data in Germany," *eTransportation*, vol. 6, p. 100079, Nov. 2020.

[21] S. Wolff and R. Madlener, "Driven by change: commercial drivers' acceptance and efficiency perceptions of light-duty electric vehicle usage in Germany," *Transportation Research Part C: Emerging Technologies*, vol. 105, pp. 262-282, Jan. 2019.

[22] Federal Motor Transport Authority. (2020, Dec.). New registrations & inventory. [Online]. Available: https://www. kba. de/DE/Statistik/Fahrzeuge/Bestand/bestandnode.html

[23] *Verwendung von Kabeln und Isolierten Leitungen für Starkstromanlagen: Teil 4*, Verband Deutscher Elektrotechniker, 2013.

[24] Deutscher Bundestag. (2019, Nov.). Ernährung, landwirtschaft und verbraucherschutz, kosten und fördermöglichkeiten von ladestationen für elektrofahrzeuge. [Online]. Available: https://www. bundestag. de/resource/blob/675848/91eb74a2dbaafe8607cf73ee9e46331f/WD-5-111-19-pdf-data.pdf

[25] Nationale Plattform Elektromobilität. (2015, Nov.). Ladeinfrastruktur für elektrofahrzeuge in Deutschland: statusbericht und handlungsempfehlungen. [Online]. Available: http://nationaleplattform-elektromobilitaet. de/fileadmin/userupload/Redaktion/NPEAG3StatusberichtLIS2015barrbf. pdf

[26] J. E. Psarras. (2008, Dec.). Selecting energy efficient distribution transformers a guide for achieving least-cost solutions prepared for intelligent energy europe programme strategies for development and diffusion of energy efficient distribution transformers. [Online]. Available: https://ec. europa. eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/seedttechnicalguideen.pdf

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