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Scope and Total Investment for a Charging Infrastructure for 100% Market Share of BEVs in Germany by 2050

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Summary

The market penetration of battery electric vehicles (BEVs) must be supported by a suitable charging infrastructure. This paper investigates the quantitative and financial aspects of an infrastructure for an extreme scenario of 100% market share of BEVs in the private transport sector in Germany by 2050, which is – assuming a constant car stock – equivalent to 42 million passenger cars. A simulation tool is developed to determine the required number of charging points and the resulting total amount of investments. According to our simulation, 40 million charging points are necessary and the total investment amounts to 80 and 107 billion euros for the best- and worst-case scenario respectively.

Keywords: BEV (battery electric vehicle), conductive charging, EVSE (Electric Vehicle Supply Equipment), infrastructure, smart charging

1 Introduction

The road transport sector is accountable for about 20% of the CO_2 emissions in Germany [1]. These emission are still showing an upward trend, which is opposing the objectives of the world climate conference in Paris, that targets a reduction of greenhouse gases by 80% in 2050 compared to 1990 [2]. To reach these targets, a fundamental redesign of the transport sector is necessary. Therefore, the traffic system's independence on fossil fuels plays a significant role [2]. Electric vehicles (EV) can drive free of local emissions and support the integration of renewable energies [3] for reduced global CO_2 emissions. Thus, electromobility could contribute to the German energy and transport transition, but requires an appropriate charging infrastructure for a successful wide-spread establishment [4].

1.1 Target setting and approach

This paper tries to give an estimate for the quantitative need and the total costs of a sufficient charging infrastructure under the assumption that all conventional cars are eventually replaced by BEVs. The paper also examines how the investments might be refinanced by the users. The path from the current situation to 100% electrification of passenger cars is not a subject of this study.

The German government's climate protection plan for 2050 states that there is a need for a rapid development of fuel and charging infrastructure for alternative fuels [2]. For further expansion, the German government is implementing a subsidy of 300 million euros by 2020 for infrastructure.

1.2 Applied data and programs

To analyse the quantitative need for charging points in various surroundings and environments, this paper uses the German national mobility study “Deutsches Mobilitätspanel (MOP)” [5]. Based on this data, the requirements for charging points and the energy demand of BEVs at their trip destinations is simulated. For estimating the charging needs for local trips (distance < vehicle range) the MATLAB-based simulation tool is developed, which uses data from the representative national travel survey MOP [6]. For long distance trips, the need for charging is assumed based on the papers [7] [8] (cf. Table 3).

2 Method for quantifying the need for charging points

2.1 Charging locations

2.1.1 Allocating trip purpose to charging locations

To determine possible locations for charging points and to identify differences in the requirements for charging infrastructure at these locations, car trip destinations from the MOP data are examined. The following Table 1 shows an allocation of the possible purposes from the MOP data to charging locations.

Table 1: Transfer of trip purpose from MOP to charging location in the simulation

Trip purpose from MOP	Trip destination from MOP	Charging location of the simulation
Work	Employer	Semi-public charging: *employer*
Education institution	Employer	Semi-public charging: *employer*
Shopping	Supermarket	Semi-public charging: *generally accessible institutions*
Leisure time	Sports center, …	Semi-public charging: *generally accessible institutions*
Home	Home	Private charging: *private parking space* OR Private charging: *shared parking space* OR Public charging: *short-distance traffic area*

2.1.2 Charging at home

Table 1 shows, that there are three potential charging locations for the purpose “home”. This refers to the parking and housing situation of households. Accordingly, we considered this in our allocation: in the MOP data, 21% of car users park their car at the roadside (i.e. public sector: *short-distance traffic area*) and 79% on private premises. Out of the latter 31% stated to park on a single reserved parking place (private sector: *private parking space*) and 69% on a shared space (private sector: *shared parking space*).

2.2 Requirements for charging infrastructure at different locations

Depending on the location of a charging point, there are different requirements for the features of the infrastructure regarding hardware and software, which have an impact on the necessary investment. Charging locations are grouped into private (*private parking space* and *shared parking space*), semi-public (*work* and *generally accessible institutions* e.g. supermarkets) and public areas (*short-distance* (so called city hubs) and *long-distance traffic* (next to highways)). Based on current market prices, literature and technical charging point requirements (e.g. hardware protection, functionalities such as authentication and authorization, the requirement of energy meters and accounting systems) an average amount of investment for each type of charging point is determined for the middle of the year 2018. The total investment in a charging point is the result of hardware investments plus “other investments” including expenses for the grid connection, the investment for the approval, planning and location search of a charging point and for assembly, construction and signage. Table 2 displays the assumptions for these requirements, which are based on market and literature research.

Table 2: Requirements for charging points at different locations

	Private sector: *private parking space*	Private sector: *shared parking*	Semi-public sector: *employer*	Semi-public sector: *generally accessible institutions*	Public sector: *short-distance traffic area*	Public sector: *long-distance traffic area*
Power [kW]	3.7 / 11 / 22	3.7 / 11 / 22	11 / 22	22 / 50	22 / 50	50
Current	AC	AC	AC	AC / DC	AC / DC	DC
Authentication & authorization	none	RFID	RFID	RFID / App / Plug'n' Charge	RFID / App / Plug'n' Charge	RFID / App / Plug'n' Charge
Energy measurement & accounting system	no	no	yes	yes	yes	yes
Hardware protection	no	no	no	yes	yes	yes
Investment in hardware (mid of 2018)	€ 733 / 836 / 1 027	€ 1 336 / 1 591 / 1 596	€ 1 787 / 1 751	€ 4 301 / 25 471	€ 4 301 / 25 471	€ 25 471
"Other investments"	€ 1 000	€ 1 000	€ 1.200	€ 2 975 / 11 900	€ 2 975 / 11 900	€ 11 900

2.3 Further assumptions (comp.)

In order to model electromobility in Germany in 2050, it is necessary to make various assumptions about the possible developments in the coming years as part of this work. Some of these can be assumed sweepingly for the simulation. In other cases, the development process is uncertain, so that the possibility of adjusting selected parameters in the simulation as well as the calculation of various scenarios seems reasonable. We therefore not only determine general assumptions, but also distinguish between two development scenarios. While the best-case scenario assumes a positive development for EV and a high degree of technical development as well as a strong decrease (see chapter 3) for the investment levels, the worst-case scenario shows opposite values. The following table provides an overview of selected variable parameters assumed for the two scenarios.

Table 3: Overview of the specified parameters for best- and worst-case scenario

Name	Best-case	Worst-case
Factor to be multiplied with total number of private vehicles in MOP data	0.95	1
Car efficiency compared to today	0.9	1
Factor to be multiplied with the reference cars' battery capacities in 2018[1]	1.5	1.2
Charging efficiency factor	90%	80%
Amount of charging points in *long-distance traffic area*	20 000	35 000

We base our assumptions on a comprehensive literature review. As we do not consider spatial limitations, one core assumption is also, that a charging spot is available whenever needed (optimistic) and charging points are occupied during the whole charging time, which is somewhat pessimistic because vehicles may be plugged in and therefore blocking charging possibilities longer than they actually need the charging point.

[1] c.f. chapter 3.1

3 Simulation of charging infrastructure

3.1 Simulation of driving behaviour

The developed MATLAB tool simulates the occupancy rate of charging points and parking spaces based on the empirical car trips and calculates the necessary number of charging points at the different locations (cf. Table 1): The actual car profiles in the MOP data, which consist almost entirely of internal combustion engine (ICE) cars, are complemented by comparable BEV characteristics. [6]. Depending on their battery capacity and car efficiency, the state of charge (SOC) is simulated for every trip and extrapolated to one sample week [6].

According to the trip destinations, the locally available charging possibilities (cf. Table 2) are modelled [9]. Considering the vehicles' SOC, the numbers of simultaneously charging cars are calculated at all times during that sample week for every location, taking into account also vehicles which continue to park after their charging process and thus block the charging possibility [9].

3.2 Calculation of charging infrastructure at different locations

For the semi-public sector (*employer* and *generally accessible institutions*) as well as for *short-distance traffic areas* in the public sector, the number of charging points is calculated as the maximum of simultaneously charging or parking after charging cars at the location during the sample week. Table 4 shows exemplarily the maxima for every weekday for *generally accessible institutions* and the *short-distance traffic area* in the best-case scenario and indicates the minimum and maximum days in one area (e.g. Saturday vs. Sunday at shopping institutions) in colour.

Table 4: Maximum number of charging points needed for every weekday in the best-case scenario

	Semi-public sector: *generally accessible institutions (shopping)*	Semi-public sector: *generally accessible institutions (leisure)*	Public sector: *short-distance traffic area*
Monday	592 057	597 863	802 430
Tuesday	455 820	844 677	902 301
Wednesday	315 289	703 566	702 113
Thursday	477 870	662 682	893 611
Friday	499 104	692 887	1 366 063
Saturday	681 197	1 194 920	1 458 103
Sunday	188 453	1 290 331	2 196 912
Maximum	**681 197**	**1 290 331**	**2 196 912**

As in the private sector (*private* and *shared parking spaces*) every BEV has its own parking space (cf. chapter 2.1.2), it is assumed to have its own charging point, too. The total number of charging points at *private* and *shared parking spaces* is therefore determined based on the number of households included into the private sector in MOP.

The amount of charging points in the *long-distance traffic area* is based on assumptions (cf. chapter 2.3).

3.3 Calculation of the amount of investments

Multiplicating the number of charging points needed at the different locations with the particular investment (cf. Table 2) considering the degression of prices until 2050, the total amount of investment is determined. This price degression is described as the exponential function

$$hardware\ investments\ (t_2) = hardware\ investments\ (t_1) * e^{-x*(t_2 - t_1)} \qquad (1)$$

with the years $t_1 = 2018.5$ (prices from middle of the year) and $t_2 = 2050$ [9]. The critical factor for the strength of the degression and thus for the level of investment in 2050 is the value of the factor x. We assume $x = 0.045$ in the best-case and $x = 0.038$ in the worst-case scenario, which causes a decrease of hardware investments of e.g. approximately 75% or 70% for 3.7 kW private charging stations in the best-case or worst-case scenario. The “other investments” are not expected to decrease. The following figure shows the price degression for charging point hardware of private parking spaces in the best-case scenario ($x = 0.045$).

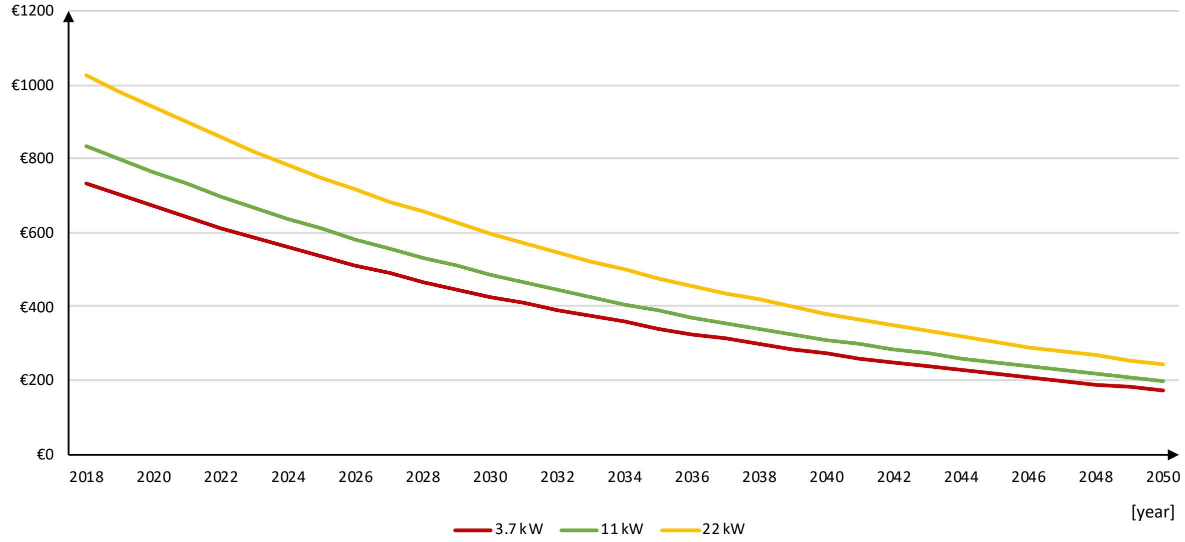

Figure 1: charging point hardware prices for private parking spaces in best-case scenario

The fees for the utilisation of (semi-)public charging infrastructure are calculated by dividing the amount of investment in the area through the number of 10-minutes charging intervals that would be realised during 10 years assuming an amortisation time of 10 years.

4 Results

4.1 Quantitative need for charging infrastructure in 2050 and total investment

For best- and worst-case scenario, about 37 to 41 million charging points result from our simulation which leads to an investment between 80 and 107 billion Euros.

The amount of investment e.g. in the domestic field is about €1 178 to €1 387 (hardware and other investments) per charging point depending on the installed charging power. The hardware investment in a 3.7 kW charging station on a *private parking space* amounts to €178 (€222) in the best-case (worst-case) scenario compared with €733 in 2018. The fees for the utilisation of semi-public charging infrastructure at *generally accessible institutions* cost between €0.03 and €0.18 for 10 minutes charging, in public areas between €0.02 and €0.10.

Table 5: Quantitative need for charging infrastructure in 2050 and total investment (best-case scenario)

	Private sector: *private parking space*	Private sector: *shared parking*	Semi-public sector: *employer*	Semi-public sector: *generally accessible institutions*	Public sector: *short-distance traffic area*	Public sector: *long-distance traffic area*
Power [kW]	3.7 / 11 / 22	3.7 / 11 / 22	11 / 22	22 / 50	22 / 50	50
Current	AC	AC	AC	AC / DC	AC / DC	DC
Share of charging points with this specific power	33% / 50% / 17%	33% / 50% / 17%	50% / 50%	67% / 33%	67% / 33%	100%
Number of charging points with this specific power	3 605 968 / 5 463 587 / 1 857 620	6 696 797 / 10 146 662 / 3 449 865	929 904 / 929 904	1 320 923 / 650 604	1 471 931/ 724 981	20 000
Total number of charging points in this area	**10 927 175**	**20 293 325**	**1 859 808**	**1 971 527**	**2 196 912**	**20 000**
Hardware investment per charging point	€ 178 / 203 / 249	€ 324 / 385 / 387	€ 433 / 424	€ 1 042 / 6 172	€ 1 042 / 6 172	€ 6 172
Other investments per charging point	€ 1 000	€ 1 000	€ 1 200	€ 2 975 / 11 900	€ 2 975 / 11 900	€ 11 900
Total investment per charging point	€ 1 178 / 1 203 / 1 249	€ 1 324 / 1 385 / 1 387	€ 1 633 / 1 624	€ 4 017 / 18 072	€ 4 017 / 18 072	€ 18 072
Total investment in this area	**€ 13 136 904 564**	**€ 27 706 349 617**	**€ 3 028 962 400**	**€ 17 064 275 263**	**€ 19 015 064 374**	**€ 361 441 490**
Total investment in all areas	€ 80 312 997 710					

Table 6: Quantitative need for charging infrastructure in 2050 and total investment (worst-case scenario)

	Private sector: *private parking space*	Private sector: *shared parking*	Semi-public sector: *employer*	Semi-public sector: *generally accessible institutions*	Public sector: *short-distance traffic area*	Public sector: *long-distance traffic area*
Power [kW]	3.7 / 11 / 22	3.7 / 11 / 22	11 / 22	22 / 50	22 / 50	50
Current	AC	AC	AC	AC / DC	AC / DC	DC
Share of charging points with this specific power	33% / 50% / 17%	33% / 50% / 17%	50% / 50%	67% / 33%	67% / 33%	100%
Number of charging points with this specific power	2 711 254 / 4 107 960 / 1 396 707	8 133 762 / 12 323 881 / 4 190 120	1 178 726 / 1 178 726	2 195 091/ 1 081 164	1 828 589/ 900 648	35 000
Total number of charging points in this area	**8 215 921**	**24 647 763**	**2 357 452**	**3 276 255**	**2 729 237**	**35 000**
Hardware investment per charging point	€ 222 / 253 / 310	€ 404 / 481 / 482	€ 540 / 530	€ 1 299 / 7 695	€ 1 299 / 7 695	€ 7 695
Other investments per charging point	€ 1 000	€ 1 000	€ 1 200	€ 2 975 / 11 900	€ 2 975 / 11 900	€ 11 900
Total investment per charging point	€ 1 222 / 1 253 / 1 310	€ 1 404 / 1 481 / 1 482	€ 1 740 / 1 730	€ 4 274 / 19 595	€ 4 274 / 19 595	€ 19 595
Total investment in this area	**€ 10 287 251 666**	**€ 35 872 642 463**	**€ 4 088 736 987**	**€ 30 567 822 802**	**€ 25 464 077 304**	**€ 685 815 369**
Total investment in all areas	€ 106 966 346 591					

4.2 Evaluation

4.2.1 Usage of MOP data is limited in *long-distance traffic area*

As explained before, the long-distance trips of the mostly ICE cars in the MOP data do not take into account the time for longer charging interruptions. Adding these charging breaks would distort the sample week trips, which are the basis for the simulation. Therefore, it is not possible to calculate the charging infrastructure for long-distance transport on this basis of the MOP data without noticeably manipulating it. The usage of the two other data sources (cf. chapter 1.2) may lead to distortions such as comparatively high utilisation of the charging points in the *long-distance traffic area* due to the inhomogeneity and incompleteness of the data.

4.2.2 Geographical analysis

As the MOP data only provide spatial information about the households' location but no geographical user data during the sample trips, it is only identified, at which type of trip destination a car is parked (e.g. supermarket). Due to this fact, a geographical modelling of the vehicles' positions is not possible in the simulation. Only the data for charging infrastructure in *long-distance traffic areas* contain geo coding. This may cause deviations (e.g. if all cars request the same supermarket but charging points are spread all over Germany).

With geographical user data, the results for the quantitative need for charging points could be improved considerably, but this comes along with a significant increase in complexity. A spatial car simulation model for the whole of Germany is currently non-existent.

4.2.3 Unrealistic basic assumption of 100 % market share for BEVs in 2050

In addition to BEVs, plug-in hybrids and fuel cell vehicles are also among the vehicles with alternative drive technologies and could make up an essential part of Germany's mobility concept in 2050. Furthermore, autonomous as well as car-sharing vehicles might reduce the overall number of vehicles considerably until then. However, they are not taken into account in this work as their share is still unclear.

4.2.4 Building of charging infrastructure during the next 30 years

The simulation calculates the number of charging points required and the investment levels for the year 2050, without taking into account how the existing charging infrastructure will change until then. Instead, it is assumed that by the beginning of 2050 all charging facilities will be installed at the respective prices for 2050 and that no infrastructure will be available before then. For more detailed results, a study on the temporal distribution of the building of charging infrastructure would be necessary.

5 Conclusion

The aim of this paper was to simulate the necessary need for charging infrastructure and the level of total investment in Germany for an extreme scenario of 100% market share of BEVs in the private individual transport sector in 2050. For this purpose, the current mobility behaviour of private car users was analysed. On this basis, six different types of charging facility locations in private, semi-public and public areas were identified. Based on specified requirements for the charging infrastructure and an estimation of the necessary investments per charging point for each type of location in 2050, the total resulting costs for a best- and worst-case scenario could be determined. The total investment of 80 to 110 billion euros can be expected for the construction of around 37 to 41 million charging points.

Information on the geographical locations of the charging cars would allow a more precise simulation of the charging point demand and therefore improve the cost estimation. Nevertheless, this study gives a plausible outlook on the charging infrastructure for electric mobility and the individual charging behaviour in Germany in 2050.

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