

Charging behaviour and energy consumption of various electric vehicles in Berlin using different charging infrastructure (slow and fast) over one year

Michael Hardinghaus¹, Marius Lehne¹, Danny Kreyenberg¹

¹German Aerospace Center – Institute of Transport Research, Rutherfordstr. 2,
D-12489 Berlin, michael.hardinghaus@dlr.de

Summary

This paper investigates charging and driving behaviour of users of electric vehicles in an urban environment equipped with different types of charging infrastructure. Furthermore, real-world energy consumption under different circumstances is analysed. For this purpose, a test fleet of seventeen different types of electric vehicles was established to record their movement and technical data over a period of one year. Results show specific patterns in driving and charging behaviour and imbalanced usage of public charging infrastructures. About half of the users almost exclusively charged their vehicle in private places; the other half uses public charging substantially. Public fast charging activities, although mostly free of charge, occur rarely and mainly in specific usage patterns. Despite varying driving patterns, most users show a similar concentration of charging activities at only a few charging locations. Findings indicate a psychological component of fast charging infrastructure. Furthermore patterns show that controlled charging in private places could move large parts of energy demand to off-peak hours and contribute to flatten characteristic peaks and troughs in the energy grid without comfort losses.

Keywords: BEV, charging, fast charge, energy consumption, fleet, GPS, public charging infrastructure

1 Introduction

The introduction of alternative electric drivetrains is the topic of intense debate from the perspective of environmental and climate protection as well as technological and economic feasibility. In addition, consumer acceptance is crucial for a successful uptake of alternative drivetrains. Various studies point out the fundamental role of company car users for near-term market success in Germany, because of their TCO awareness, their homogeneous driving profiles, and their possibility to charge the vehicle at company facilities [1-3]. These studies have found out that commercial passenger cars are a key early market segment for plug-in electric vehicles (PEVs). Compared to privately owned vehicles, the commercial vehicle segment is also characterized by higher mileage and a higher share of vehicle sales in Germany. Up to now, there have only been a few studies analyzing the commercial passenger car sector, and which arrive at contradictory results due to insufficient driving profile data [4]. Furthermore, most of the existing studies are based on small samples with short data-collection periods [5, 6]. Real-world energy consumption across all seasons and knowledge of the driving and charging behavior of different company car users are thus determining factors, and are therefore the focus of this study.

2 Methodology

2.1 Study set up and background

To address diverse questions in the thematic area of electric vehicle usage and public charging infrastructure, a test fleet of seventeen electric vehicles was set up. The vehicles were used by various commercial customers from the sectors social care, taxi, media, handicraft, energy supply, science and hotel business. Most vehicles were used as ordinary company cars including private journeys by employees. The test fleet consisted of 10 BMW i3, 3 VW e-Golf, 2 VW e-up and 2 smart ed. Furthermore, surveys were conducted to investigate drivers' attitudes, preferences and self-assessments concerning mobility behavior. To explore changes over the period of usage, surveys were conducted twice, at the beginning and after using the vehicle for about nine months.

In 2015, in the study area of Berlin, a public charging infrastructure in Berlin was available. A total of about 500 public charging stations operated by different companies were on hand to meet the demand of roughly 2,000 registered electric vehicles [7]. During the duration of the study, the expansion of public charging infrastructure speeded up following a systematic demand-driven approach [8]. Apart from additional public charging points with regular charging capacity, 13 fast chargers were available when finishing the data logging. As this study was conducted to test the CCS (combined charging system) public charging infrastructure under construction, utilization of public fast chargers was free of charge. Billing had been implemented only at some stations by the end of 2015.

However, previous studies had found out that most of charging processes take place at home or work [9]. Hence, in this paper we analyze the charging behavior of the different company car users in more detail, especially with consideration of the recently installed CCS fast charging infrastructure in Berlin.

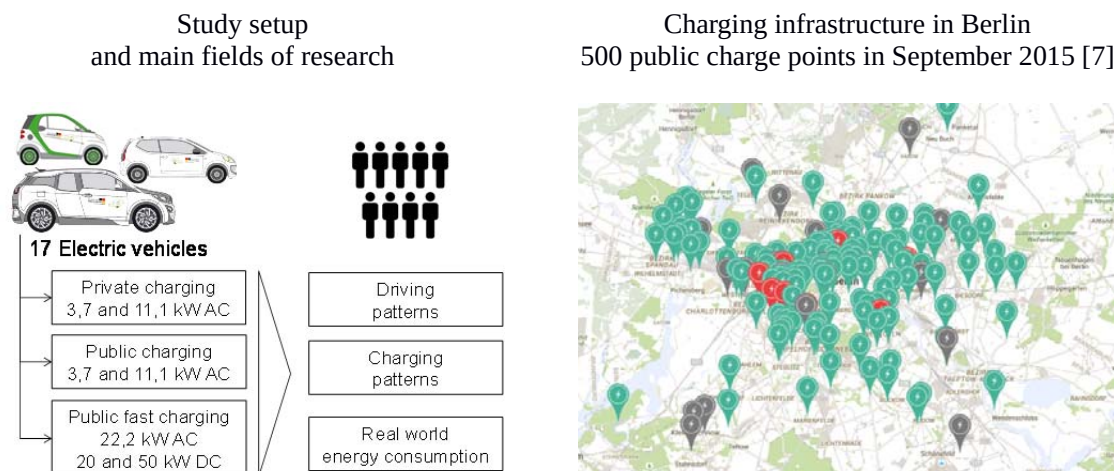


Figure 1: Study setup and status of charging infrastructure in Berlin in September 2015

2.2 Data availability and reliability

This section gives an overview of the type, nature and amount of data used to obtain the results.

2.2.1 Vehicle Measurements

In modern vehicles, control devices communicate with one another via the CAN. Although the basis protocols are standardized, the data themselves are proprietary, treated as confidential by vehicle manufactures, and not made readily available to external projects. The National Organisation Hydrogen and Fuel Cell Technology has established a consensus between research vehicle manufacturers covering all projects, in which the participating parties reached an agreement on a dataset for driving and charging cycles to be offered by all manufacturers, known as the minimal dataset. Data for research institutes are collected on the basis of this consensus and the corresponding bilateral agreements with manufacturers.

In the vehicle, an embedded symbol is installed which communicates in two directions: with the vehicle via the CAN, and with the IT backend via 3G mobile networks. The system is configured specifically for the vehicle type. This particularly concerns data recording, though also aspects of power management – under what conditions the system starts and stops – and how the driving and charging cycles can be distinguished. In the process, sixteen and seven parameters are recorded in the driving and charging cycles respectively. The data encompass, for example, mileage, speed profiles, energy balance, charging performance, time, environmental temperature, and GPS position, the latter as a rule at the beginning and end of a cycle and in min./max. values.

2.2.2 Data quality

Overall, the technical processes can vary a lot depending on vehicle type and charging infrastructure. In addition, many manufacturers do not support the full minimal dataset, using intellectual property to justify this. A critical example of this is battery temperature. In detecting cycles, the driving cycle is easy to spot, with its switching on and off of the ignition. With the charging cycle, there is no comparable signal to interpret. An alternative observation is thus made: charging cable plugged in and charging session active. The charging process can be interrupted by the infrastructure or the vehicle, particularly when these initiate changes to the charging current. These amount to regular, deliberate breaks that can tend to happen more often at the end of a charging procedure. Since it is difficult to be certain such an interrupted session actually amounts to one contiguous charging, the system technically recorded several charging sessions per procedure as perceived by the customers.

Battery capacity and the state of charge (SOC) form the basis for calculating consumption. In most cases, only those SOC's are made available on the CAN that are also visible to the customer in the vehicle. This can involve deviations from the real charging status of the battery. This results in lack of precision in consumption and charging procedures.

Auxiliary consumers can play a big role. There is no formula for any vehicle type for calculating total consumption by adding together individual auxiliaries and drive unit. In part, this information was not revealed, in part it is not available in the vehicle.

Due to delays and limitations in quality of recorded data, the full period of one year data logging could only be achieved with the Smarts. The period of appropriable data was shortened to nine, respectively eight month for VW and BMW.

2.3 Data Preparation and Processing

2.3.1 Data Pre-processing

In a first step, we remove from the data implausible records and artefacts created in the recording stage. Additionally, records are removed which are incomplete regarding our analyses. Records of activities shorter than a minute are discarded. This is because the recording device needs about the same time to boot. Therefore the data quality of very short activities cannot be ensured.

The second pre-processing step is to separate charging activities from driving activities. Charging activities are characterized by an overall positive energy total and by zero distance travelled. Driving activities on the other hand are characterized by a distance travelled as well as a negative energy total. There are 510 records that cannot be clearly classified as either charging or driving activity, as both go together because of failures in separation during data recording. These records can only be used for analysing movement patterns. But they are excluded from analyses regarding energy consumption. This is because, through data aggregation at the measurement unit, it is not possible anymore to attribute characteristics of the activity to either the charging or the driving process.

There are cases where multiple records are created for one charging activity. This happens because the charging infrastructure or the car interrupted the charging process. This process is then resumed at a later time point. Thus, we merged multiple records into one if either no driving activity was recorded between two or more records, the time period between the end of the first and start of the second record was less than one hour, or there was no significant change in the vehicle's position. In summary during the observation period we obtained 41,864 records, after data cleaning we obtained 16,785 records of sufficient quality.

2.3.2 Location Clustering

Each recorded activity is associated with two geo locations, which are measured via GPS. We assign these recorded locations to points of interest. In the case of charging activities a point of interest corresponds to one charging station or multiple charging stations if they are at the same site. For each driving activity we assign the start and the end of a trip to a point of interest. This includes, for example, the places of work and residence. For each of those places, only one point of interest should exist. A method that identifies these points of interest must be able to cope with the inaccuracies of the location measurements. Also, the shape of a point of interest can vary. For example, a user can park his vehicle in front of the place of work as well as on the property. Both locations should correspond to the same point of interest. Except for the position of the public charging infrastructure, we have no further data available about other points of interest. This is why we chose a data-driven approach, in which clusters of recorded locations are created.

In principle our method is based on the DBSCAN clustering algorithm [10]. Each point has a specified range in which other points are assigned to the same cluster. If a point is assigned to one cluster, then all its neighbours lying in the range of that point are also assigned to that cluster. Additionally the original algorithm requires that a minimum number of points need to be located within this range before the cluster is extended with the new points. We simplify this idea by setting the minimum number of points to one. As a result we obtain clusters where the convex hull of all member points can form various shapes.

Every cluster identified by the algorithm corresponds to a point of interest. As the range we chose 100 m. This is enough that uncertainties in GPS measurements are accounted for. It is small enough such that there is no grouping of different locations into one mixed location. One main advantage of this approach is its flexibility. It is possible to have points of interest that correspond to a larger area, such as a parking lot, as well as points of interest that cover a more concentrated area, such as a charging station. For visualization and further analysis we assigned a representative point to each cluster. This representative point is the mean of all points assigned to this cluster. Based on this method, it is feasible to overestimate public charging as private charging locations in the surroundings of a public station might wrongly be classified as public.

2.3.3 Charging Type

For investigating the charging behaviour of the participants, we differentiate between the accessibility of the charging stations. Further, we determine if the fast or the regular option was chosen for the charging activity. For each charging location we determine if it is publicly accessible. This is the case when the representative point of the corresponding point of interest is within 100 m from a public charging station. The minimal data set does not provide any direct information about the infrastructure used for charging. For each charging activity, we estimate if the user was using a fast charging option. For this we calculate how much energy was charged in the time period of the activity. If the resulting capacity is larger than 11.1 kW, a fast charging option was chosen. Because charging-activity length is determined by the time the vehicle is plugged into a charging station, we do not identify all activities at fast chargers. But we detect all those activities in which the car was plugged in for a shorter time than would have been possible to charge the same amount of energy using regular chargers. In other words, such activities in which it was worth choosing a fast charging option over the regular charging option.

3 Results

3.1 Charging behaviour

The energy supply of electric vehicles is one major difference to vehicles powered by combustion engine. Unlike the refuelling of fossil fuels in conventional vehicles, energy transmission can be carried out in various ways, including differentiation by charging capacity and charging location (see Figure 1). Furthermore, due to smaller range and longer duration of energy transfer in battery electric vehicles, charging plays an outstanding role in operating electric vehicles. The following analyses deliver an insight into how the participants of the study organized charging their EVs, and what differences, similarities and patterns can be observed.

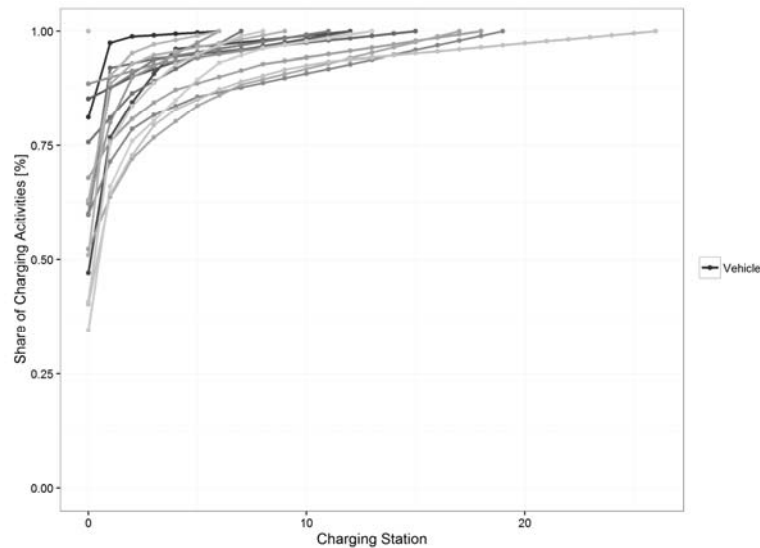


Figure 2: Share of charging activities by number of different charging locations used per vehicle

Figure 2 shows the share of charging activities by number of different charging locations used. Each line represents a single vehicle. It is obvious that, for the majority of vehicles, the vast majority of charging activities are located at a few stations. For example, for ten out of seventeen vehicles, 90 percent of charging processes take place at up to 6 locations. On the other hand, one vehicle of the fleet uses a total of 27 different locations for charging. Regarding the long period of data recording, the results show relatively stable charging behaviour. When analyzing energy demand instead of the number of charging events, the results appear even more concentrated and the majority of energy demand is supplied at very few locations.

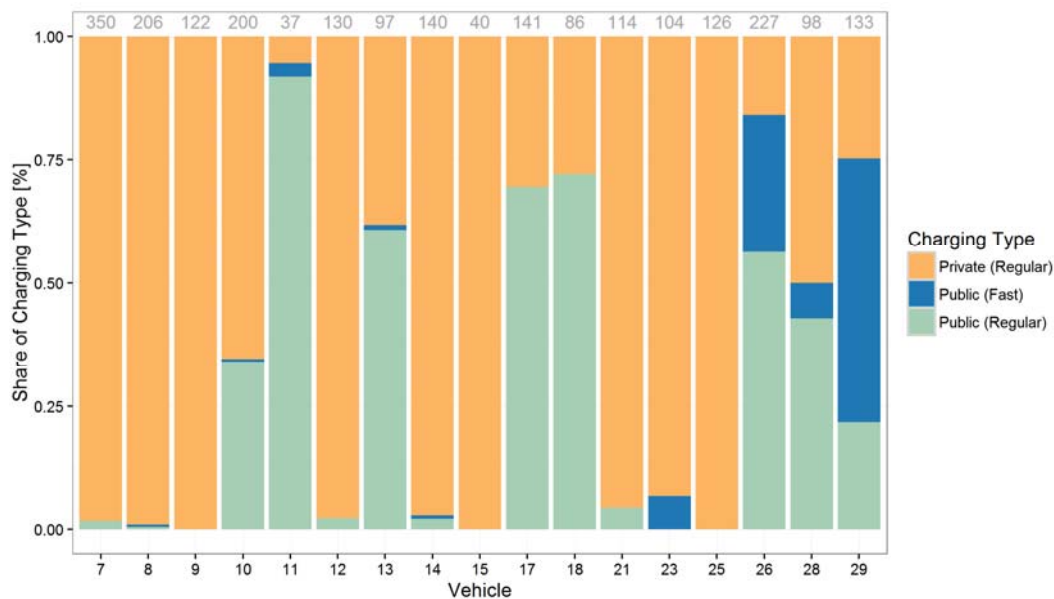


Figure 3: Shares of regular private and public, and fast public, charging

Figure 33 shows the percentage distribution of charging processes performed in private places (orange), at regular 3.7 kW or 11.1 kW public charging stations (light green) and at fast public charging stations CCS (blue). A charging process is classified as public when, in a range of 50 meters around the center of the recorded spatial charging cluster, a public charging station is located. A process is classified as public fast (or CCS) when a known CCS-charging point is located and the charging power is higher than 11.1 kW AC. In this case charging is done at 22.2 kW AC, or at 20 kW up to 50 kW DC. Compared to public categories, private charging includes all locations without public charging stations. Above each column, the total number of charging processes are noted, below, the vehicle number is indicated. The strongly diverging

number of charging processes executed by individual drivers is to be borne in mind when interpreting. From a total of 2396 charging processes recorded, 538 are classified as public charging and additional 153 as fast charging.

The data show a clearly uneven distribution of usage of public charging infrastructure among individual users. About one half of the users did not use public infrastructure at all or used it a very little amount. However, six users show predominant usage of public infrastructure. This includes one test user holding a publicly accessible charging station on his premises, which is classified as public. One vehicle was charged almost exclusively at public charging stations.

When differentiating public charging processes in terms of charging speed, usage of fast charging can be identified. As shown, about half of the users made some kind of use of the fast charging option. A closer look into the data shows that the majority of fast charging processes, regarding the total amount in the study and share of individual user, were performed by two vehicles used as taxis (vehicle 26 and 29). According to this, a total share of 88% of all fast charging activities in the fleet were performed by the two taxis.

When being surveyed about the importance of fast charging, the majority of the test users attached high importance to public fast charging infrastructure. Figure 4 shows the indicated importance of the fast charging options at the beginning of the period of usage (T0) and after 9 months of using the EV (T1). As is apparent, the importance is named as high but shows a decreasing tendency when becoming familiar with the vehicle.

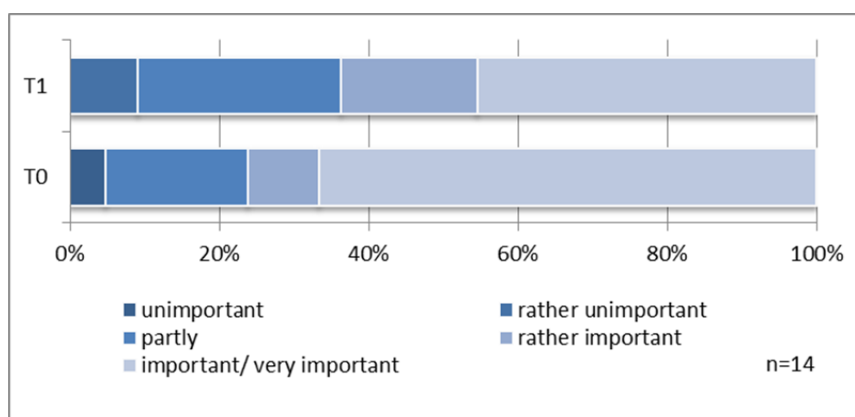


Figure 4: Indicated importance of fast charging

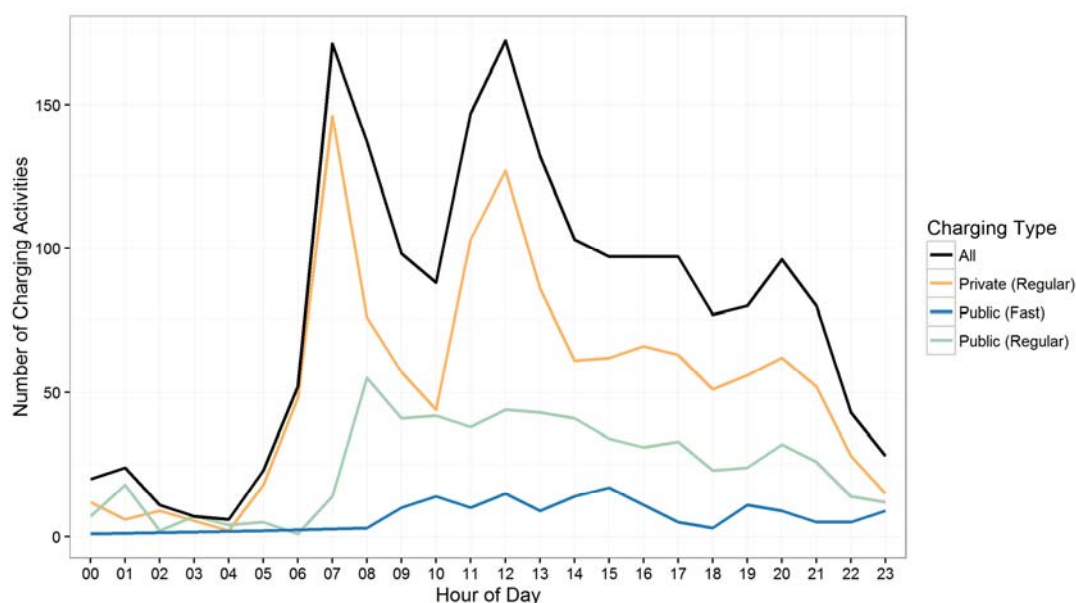


Figure 5: Charging activity by time of day

Figure 5 shows the time course of charging processes in terms of when they were initialized. The data show two high peaks, one at 7 AM and one at 12 noon. The oft-reported evening peak appears to be very small in total. As expected in commercially used vehicles, charging in the daytime is clearly predominant because of the low prevalence of home-charging overnight. Comparing public charging and private charging, public charging looks more constant during the daytime. The analysis of charging processes in the course of the week shows corresponding results: low activity outside the working hours. Private and regular public charging decrease by more than 50% on weekends, fast charging stays relatively constant. Regarding the different prevalence of charging types in different usage patterns, the stability of public charging activities is shaped to a large extent by taxis.

The overall picture is thereby made up of individual courses. Differentiated between individual vehicles, two essential patterns are clearly recognizable. The majority of vehicles show distinct characteristics with strong peaks in both charging and driving activities. A driving peak is often followed by a charging peak, which means that after a regular journey the vehicle is connected to the grid. As this is often not followed by driving activities, energy supply could be controlled and stretched. A smaller part of the fleet shows less constituent behavior and smaller peaks spread over the course of the day. However, only three vehicles showed substantial charging activities in the late evening or at night.

3.2 Charging Patterns

Figure 6 shows representative charging and driving patterns of four individual users. Green dots mark trip destinations without, red dots destinations with charging processes. The size of symbol is equivalent to the quantity of charging processes. Lines show relations between locations visited. Top left is a vehicle used in home care social services, mainly in one district of Berlin. All charging processes take place on the premises of the operator, which functions as hub of the activities. Top right is a company car used by a tradesperson, who uses the car mainly for a long commuting distance. Some journeys are also traveled in the surroundings of the place of work and the place of residence. For the majority of energy demand, the car is charged at both places, at home and at work. Some charging processes, however, appear at one public fast charging location. In terms of charging patterns in the test fleet, these two patterns represent more than 75% of the vehicles. The vehicles are charged exclusively at up to three locations, or these locations are clearly predominant, for the vast majority of charging processes (see also Figure 2). Thereby, using a smaller number of primary charging locations is more likely for each vehicle. Although a clear predominance is obvious, some vehicles show substantial use of further charging locations. Of particular interest is the similarity of spatial charging characteristics in a large part of the group despite strongly diverging driving patterns.

The pattern below left shows the data recorded by a taxi. Characteristic here is the broad distribution of destinations, especially in the inner city of Berlin. The taxi is charged on the operating companies' premises and at a couple of public stations in the inner city with substantial share of fast charging. The patterns of two taxis in the fleet operated by different companies show close matches in terms of both charging and driving patterns. Not considering charging speed, the pattern of using several charging stations without a clear prevalence is seen in four vehicles, including two taxis.

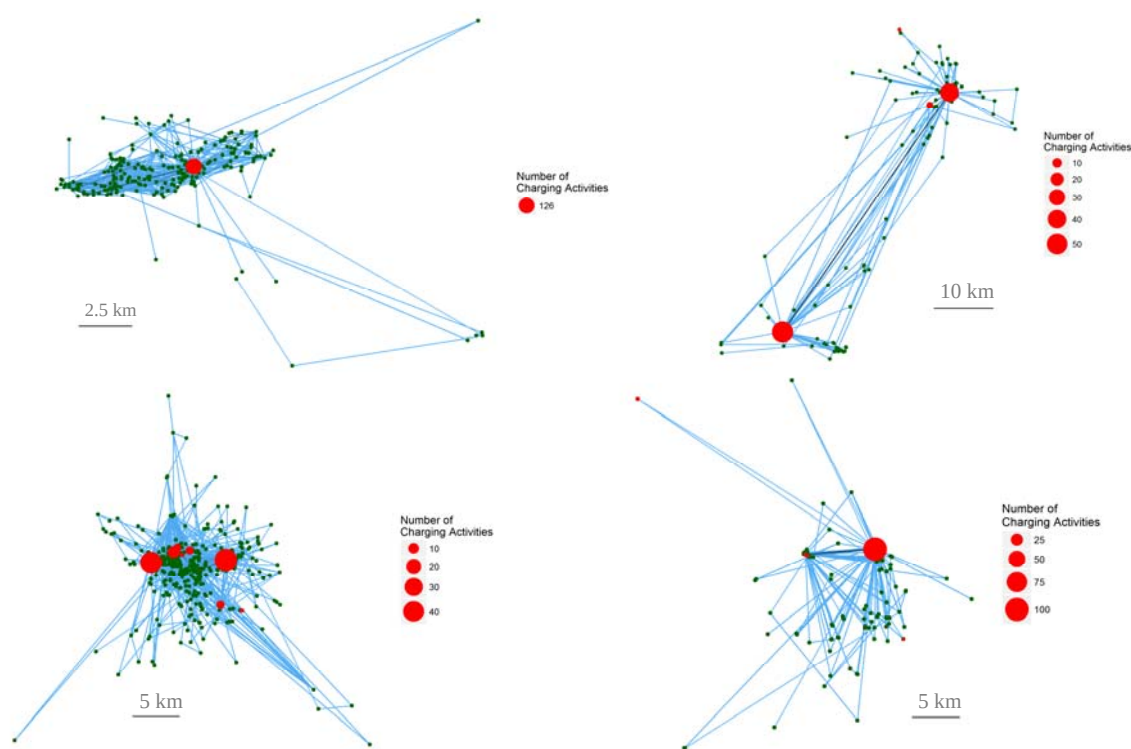


Figure 6: Selected charging patterns

3.3 Energy Consumption

Trips were categorized based on the minimum outside temperature recorded during the journey. The trips were collected in 3° bins. For each bin the average energy consumption was calculated. The smoothed line in Figure 7 was created by local polynomial regression fitting.

Bringing together energy consumption and outdoor temperature, correlations as expected are found. The highest efficiency can be found at about 18° , higher and lower temperatures are accompanied by higher energy consumption. As shown in Figure 7, this relation can best be seen using the example of Volkswagen vehicles. The lower dependency observed in other vehicle models is likely to be an incomplete measurement in terms of auxiliary users (see section 2). Furthermore, because of rare data logging for BMW in summer, there are only a few observed values on very warm days for this type. Here further is research necessary.

However, the observed correlation has considerable implications, as consumption is more than doubled when comparing favourable conditions with the worst conditions recorded. Analysis examining energy consumption in the course of the year draws a similar picture, with higher consumption in winter and midsummer. Comparing energy consumption data logged in real-world conditions (city) to manufacturer specifications, Volkswagen vehicles were unlikely to achieve combined values of New European Driving Cycle (NEDC), which are 11.7 kWh/100km and 12.7 kWh/100km for VW's e-up and e-Golf respectively.

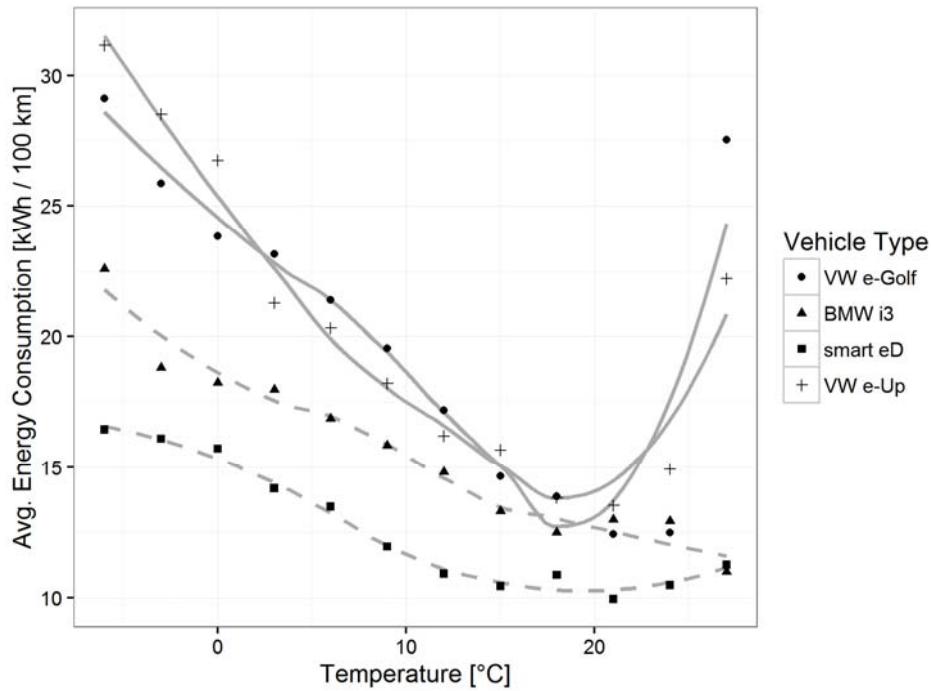


Figure 7: Energy consumption based on temperature

4 Conclusion

The analyses show the charging behaviour and energy consumption of a real world fleet of electric vehicles in the city of Berlin, Germany, over a period of one year. As real-world energy consumption and integration of charging activities are important aspects of the usability of electric vehicles, these topics are stressed. Overall, the results show similarities and differences in both behaviour and technical parameters.

Regarding driving patterns, a wide variety of behaviours is seen. In contrast, in terms of charging patterns, the broad majority of users show relatively similar behaviour, using very few charging locations for the majority of charging demand. Thereby, the role of public charging is strongly imbalanced. For over half of the vehicles in the test fleet, public charging played a minimal role while, for others, public charging makes up large percentages. As to public fast charging, our results show that, for the large majority, this option does not play more than a supplemental or potential role. Half of the users did not use the public fast charging infrastructure at all. This is even more meaningful with respecting to free-of-charge use of public fast charging stations during the duration of the study. For the majority of tested use cases in this study, the utilisation of public fast charging infrastructure was factually not important in total. Compared to the attached importance of fast charging, indicated in direct survey, the discrepancy between desires and behaviour is likely to strengthen the dominance of the psychological component of public fast charging infrastructure and its role as backup option. These results suggest that charging behaviour is strongly integrated in daily routines, using primary charging locations. This supports the view of a mobility behaviour that is strongly based on routines and convenience. Users seem to integrate charging necessities in the day-to-day routing using existing parking hours of the vehicle.

On the other hand, some individual users used of public infrastructure substantially and seem to strongly depend on it. If we focus on public fast charging, specific usage patterns, such as those of the taxis in this study, involved substantial usage of public infrastructure and seem to strongly depend on the high charging capacity, as charging processes were followed by further trips and the vehicles are used intensively. It seems likely that, with the further expansion and greater reliability and level of awareness of the public fast charging infrastructure, more users in such patterns might consider the switch to electric vehicles.

Considering the time course of charging processes, the little importance of home-charging in the test fleet becomes apparent. This is not unexpected, as all vehicles are registered as commercial. Compared to a prevailing overnight home charging behaviour in privately used EVs, the observed charging demand seems to boost peak loads, particularly in the morning, in the energy grid. Consequently, intelligently controlled charging could be a way to flatten the peaks of energy consumption. In individual time course patterns,

charging peaks are often followed by longer driving troughs, which proves the potential of controlled charging without disadvantages for parts of the fleets. Results also show that, for vehicles used irregularly day-to-day, controlled charging is not likely to bring general benefits as there are no clear time recognisable patterns. As most vehicles are rarely used during off-peak hours, there seems to be a large potential to move energy demand to early morning hours. However, these results need further research with respect to energy flow. Intelligent metering and appropriate billing models could support overnight home charging behaviour for regular company car use (including trips home).

As described, data recording works differently depending on the individual vehicle type, and complete data is not always accessible due to manufacturer-specific restrictions. Together with a modest sample, this might lead to limitations in data reliability. On the basis of the limited sample size and specific usage profiles, the present results and conclusions might not be representative for a large EV-fleet. For further internal research and publications, a database at DLR merges two projects with a total of about 140 electric vehicles in different usage patterns.

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Authors



Michael Hardinghaus studied geography at the Humboldt University in Berlin. Since 2011 he has been working as research associate at the German Aerospace Center. He has developed methods to design location concepts for public charging infrastructure and deals with questions regarding infrastructure development in general.



Marius Lehne holds a degree in business informatics from the Westfälische Wilhelms-Universität Münster. He focusses on the analysis of big data and movement data.



Danny Kreyenberg studied industrial engineering and management. He holds a PhD from the Karlsruhe Institute of Technology (KIT) for his research on electric vehicles and their marked potential. He worked several years in the automotive industry in R&D and production departments. His current research focuses on electric vehicles and their charging infrastructure as a scientist at the German Aerospace Center.