Technical Data Analysis and Power Grid Effects of Fast Charging Processes of Electric Vehicles

Georg Göhler
University of Stuttgart IAT
Mobility Concepts and Infrastructure
Stuttgart, Germany
georg.goehler@iat.uni-stuttgart.de

Lukas Effing
University of Stuttgart
Stuttgart, Germany

***Abstract*—The competitiveness of electromobility is strongly influenced by the charging procedure, whereby particularly fast charging emerged as key factor for user adaptation. At the same time, a rising number of used electric vehicles (EVs) would considerably overstrain the existing energy infrastructure. Especially the short-term peaks arising from fast charging technologies are most challenging in this regard. To assess the impact of the rising EV loads on the distribution network several methods are suitable to gain a better understanding, due to which especially computer-aided simulations became a widespread approach. In contrast to complex battery and energy load simulations, this paper[1] aims to evaluate electromobile grid impacts in high accuracy by means of extensive field tests. The present paper provides new insights in load behaviors of different EV-types by depicting influencing factors like state of charge (SOC) and temperature dependencies. A thorough analysis of 263 charging events is carried out along with an evaluation of the system load on the Fraunhofer IAO Micro Smart Grid to outline the challenges future power grids are faced with. The main findings of this work are, that each EV model features a distinct charging profile, by which a progression with the charging and battery technology can be noticed. Additionally, a strong difference between charging events of the several seasons of the year was shown with a decrease of charging power in winter. It can be concluded, that fast charging imposes a huge burden on the energy grid due to the high peak loads, which is the main challenge for the widening EV fast charging implementation.**

***Index Terms*—electric vehicles, micro smart grid, fast charging, dc charging, battery temperature, SOC, cosφ, load profile, Matlab®**

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I. Introduction and Recent Developments

To achieve international climate protection goals and compensate for the reactive increase of fluctuating power generation from renewable energy sources, an accelerated development of electromobility is indispensable. For now, electric cars provide a substantial energy efficiency advantage compared to internal combustion engine (ICE) cars, tripling the engine efficiency [1]. In line with these trends the electric car market will accelerate to a mass market adoption in the next 10 to 20 years [2], [3]. For the global adoption the IEA has made several projections like the "Reference Technology Scenario" shown in Figure 1 that combines multiple estimations based on energy goals for diversification, energy efficiency, decarbonisation and air quality.

Yet the acceptance and competitiveness of electromobility is sharply influenced by the charging infrastructure and the procedure, whereas fast charging emerged as a key factor to user adaptation. The easy accessibility to rapidly increase one's travel-range through recharging, essentially mobility itself, can be provided by the fast charging technology. Even if the quick charger is not actively used by the drivers, it may promote the EV usage by compensating the lack of battery capacity, i.e. essentially driving range for the user [4]. A possible target to meet the replication will be a recharged range of 100km in a time of 10 minutes [2]. As Christensen and Weiller estimate, the percentage of car owners that would require solutions for fast charging is between 20% to 29% [5], [6].

However, there are further crucial obstacles that need to be overcome for quick charging to contribute to the market penetration of EVs. Excessive power drain can be caused through short term peaks in momentary charging power, thus overloading the energy grid. Research shows that the new loads that are going to be incorporated into the energy grid will be manageable and not emerge as the heart of the challenges for the energy network [4], [7]. For the IEA's two-degree-projection of EVs and plug-in hybrid electric vehicles (PHEV) the additional loads that need to be met are only 1.5% of the total electricity demand in the year 2030 [2]. Nonetheless a momentary noticeable impact of EV charging on the distribution level of the grid is expected, especially resulting from local hotspots and clusters that aggregate to greater peak loads. This phenomenon will further increase due to multiple parallel fast charging processes with higher peak and higher average power levels, magnifying the ruggedness of the daily load profile [2], [7].

With electric vehicle technologies still under strong development as well as standardization and platforms, OEMs offer diverse approaches to quickly charge the vehicles' battery. Previous observations have been made based on load models, estimations and stochastic calculations lacking the consideration of an inhomogeneous electric car market and the underlying differences of the models. The rise of the EV model variety is depicted in Figure 1. These differences, concerning for example the load behavior, aggravate direct generalization and must be considered for the optimal planning of charging infrastructure. Hence this produces an outstanding need for a wide analysis regarding the effects

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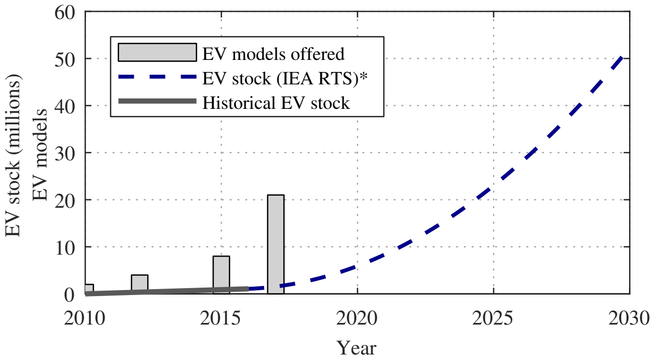


Fig. 1. Deployment scenario for the EV stock by 2030 and the offered distinct EV models [1], [2], [8]
*International Energy Agency Reference Technology Scenario

of the varying fast charging procedures and an evaluation of factors that are influenced by the diverse EV models, as well as the aligning impacts on the electricity network.

The paper expands its new insights in the mentioned issues as follows. Current knowledge provided in literature relating to the analysis of load behaviors of different EVs, the load profiles of (fast) charging stations and the state of the art for fast charging systems is given in section II. Section III covers the structure of the data analysis as well as the methods used. The next section IV presents the gained insight for different EVs and the factors discussed in II. The last section V discusses the results, summarizes and offers final conclusions based on this study.

II. State of Technology and Research

For the European market the only available standard concerning the charging power, plugs and sockets is specified in the IEC 61851. It differentiates four different modes including 3 AC and 1 DC connection and further associates them to a power category [9]–[11]. These modes need to be exploited when charging strategies and load models are planned, as each level offers unique characteristics. Mode 1 to Mode 3 specify AC charging and offer a power of up to 43.5kW with a 3-Phase connection, however this charging power is not yet common. Mode 4 on the other hand specifies high power fast charging for an external charger with a DC connection. This paper sets the focus on mode 4 DC fast charging as this mode offers highest technological potential for public charging, has the current highest power rating and is currently used in a lot of cars for the quick charge [12]. For this paper fast charging is used analog to the DC high power classification rated superior to 22kW and thus corresponds to the definition of the EU directive "on the deployment of alternative fuels infrastructure" [13]. Thereby the most common EV plugs used are the Combined Charging System (CCS), respectively the Combo Type2 for the European market specified in the IEC 62196 standard, and CHAdeMO defined by the CHAdeMO Association [10].

Recently a lot of research activity is targeted to clarify the impact of the rising EV load on the distribution grid in the next years. Therefore several methods are used to gain insight, whereby the way of simulation is a widespread one. For the approach of modelling the distribution grid and the fast charger, detailed results can be found. These were obtained through a multistaged simulation [7]. Others have offered a complex model of a fast charging station in order to more closely represent the newly introduced EV load [14]. The paper concludes that EV load greatly influences the margin of power system loading on the grid and suggests that the load behaviors of EVs are considered while planning the charging infrastructure to reduce system inabilities. As stated the practicability of these models is highly dependent on their accuracy, hence as no real world data was used, it leaves the need for a verification through a study. At the same time, since the design of the internal circuits of a fast charger is no topic in the current standardization process, parameters including reactive current and following $\cos\varphi$ may sharply vary between manufacturers, making it difficult for a general model without a real comparison [4]. Further Weiller states that the long-term increase in power demand resulting from EV charging might not lead to a significant challenge for the electricity grid or distribution security, as the vehicle charging share might only rise to 5-8% by 2030 [6] whereas other estimations deliver even lower numbers [2]. But this assumption needs to be supplemented by a consideration of the effects of peak-demand. Fast charging scales up the momentary charging power, which can effect such peaks, especially with multiple parallel charges at 50kW or higher [15], [16]. Numbers for a peak load increase due to high power charging range from 50% to 62% depending on the usage scenario [6]. This effect is highly contingent on the single charging profile of an EV model that itself offers the potential to further increase the peak. Hence there is a great need for a systematic comparative analysis of different EV models considering the effects of fast charging and their affiliated charging profiles. An other useful approach was made with data of work and rural area charging processes [17], [18]. This paper makes use of its structure for the first viewpoint in section IV-A.

In addition, an integration of a fast charging station in a micro smart grid (MSG) with an energy storage system (ESS) was able to provide the power exceeding the set threshold, hence to smooth out the high power demanding peaks. Consequently the risk of overstraining the grid can be significantly reduced [11]. To make greater usage of this concept EV characteristics need to be provided as for the one vehicle used in the paper; multiple charging curves can solidify this approach.

Besides simulations for a usage extrapolation [19], other papers used current non-EV driving data [6], [16]. These approaches depend highly on the chosen model parameters, hence demanding an observation of empirical data from a fast charging post with diverse EVs connected over time. Furthermore there is a lack of research regarding occurance and change of quick charging aspects including the EVs' battery temperature, the stations' reactive power and $\cos\varphi$ and seasonal differences [19] and their connection to the grid effects.

III. Methodology

In contrast to complex battery and energy load simulations, this paper uses the approach of an extensive field

TABLE I
ELECTRIC VEHICLES USED IN THE STUDY[a]

EV	Connector	max. Charge Rate [kW]	Nominal / (Real) Battery Capacity [kWh]	max. Range (NEDC[b]) [km]	Release Year	Fraction of Charges
Nissan Leaf	CHAdeMO	50	24 / (21.4)	175	2011	51.5%
Mitsubishi iMiev	CHAdeMO	50	16 / (15.6)	150	2010	28%
BMW i3	CCS	50	33.2 / (27.2)	300	2016	20.5%
VW eUp	CCS	50	18.7 / (16.3)	160	2013	-[c]
VW eGolf	CCS	50	24.2 / (21.1)	190	2014	-[c]

[a]The information was obtained through various sources including the corresponding OEM websites.
[b]New European Driving Cycle
[c]Only few charges were performed as a comparison for the other EVs.

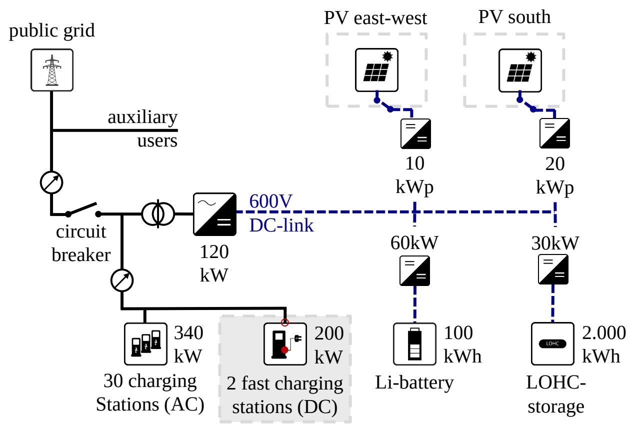


Fig. 2. Overview of the Fraunhofer Micro Smart Grid

test. To examine the actual energy network loads and the underlying vehicle determinants of the charging process, a fast charging station was set up in course of project SLAM. SLAM seeks to ensure the energy supply of EVs through the construction of nationwide charging infrastructure, especially DC fast charging, and to improve the attractiveness of electromobility through the easy accessibility rapid charging procedure [20]. Suitable for planned analysis, the installed system offers a power of up to 150kW and was integrated into a Micro Smart Grid shown in Figure 2 for evaluation of effects on the supplying energy network. The observed fast charging station used for this paper with the ability to charge with powers of up to 150kW is highlighted in light grey.

A. Data basis

The study was conducted to examine two main sides of the charging procedure. Firstly, the exchanged information of the station and the connected EV, as well as the status of the battery were recorded to provide the basis for an analysis of the vehicle-side effects and crucial factors (see figure 2: red dot). Secondly, a data logger at the grid connection of the charging station was used to identify influences on the network-side of the charging station, respectively on the smart grid (see figure 2: red circle). 263 fast charging processes of several EVs of different generations with the constant given infrastructure were recorded between December 2016 and July 2017 to gather the underlying data. The used EV fleet can be considered as a replication of the market as it represents different price spectra, battery capacities, driving ranges, sizes, release years and the connectors CHAdeMO and CCS. The selection consists of models of high relevance for the German market based on share of the monthly registrations. With an observation of the vehicles shown in Table I, namely BMW i3, Nissan Leaf, Mitsubishi iMiev, VW eUp and VW eGolf, a statement for a total of over 30% of the electric cars registered in Germany in the first half year of 2017 can thus be made [21]. This creates a broad, statistical basis that further emphasizes the relevance for the general EV market and opens the possibility to make general assumptions for the electricity grid on a national level. For the further proceeding, in accordance with research on data science [22], the data is first pre-processed for accuracy and continuity to an appropriate shape. Then the analysis is conducted as explained in III-B and finally visualized for the presented plots.

B. Structure of the data analysis

Due to the extended nature of the data a threefold analysis is conducted, specifying different viewpoints that were proven essential in the section II. Firstly this paper considers the entire fast charging system as it is highlighted in grey in Figure 2 as well as its connection to the grid, respectively the micro smart grid. Secondly, a more detailed perspective shows the different charges for the EVs. Thirdly, specific key factors for the charge and the grid are examined. The entire outcome can be again abstracted and used for more detailed and realistic models to show influences on the energy grid. This way insight into the entirety of the charging process can be made possible.

Considering the first viewpoint, an overview of the entire period under review time of the study is made to meet the need for empirical data as depicted in section II. A load profile for the charging post with confidence intervals and the average load is generated and statistical distributions are evaluated to provide the basis for the methods for the second viewpoint.

For this purpose an observation concerning the differences of EV models during the fast charging process has been conducted. This viewpoint aims to show the model variations that need to be considered while planning charging infrastructure. The data for the first three cars mentioned in Table I is broken down based on influences mentioned in Section II and then compared to each other as well as to the reference

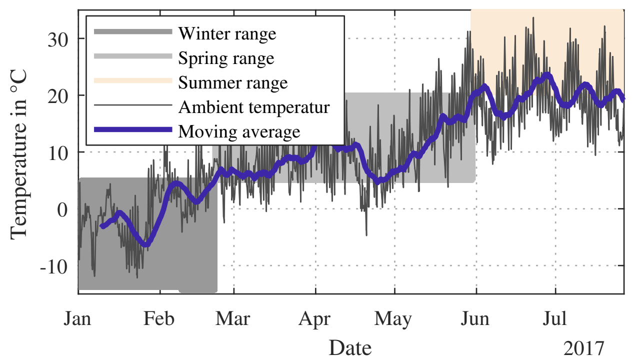


Fig. 3. Course of temperatures over the year and the classified temperature ranges

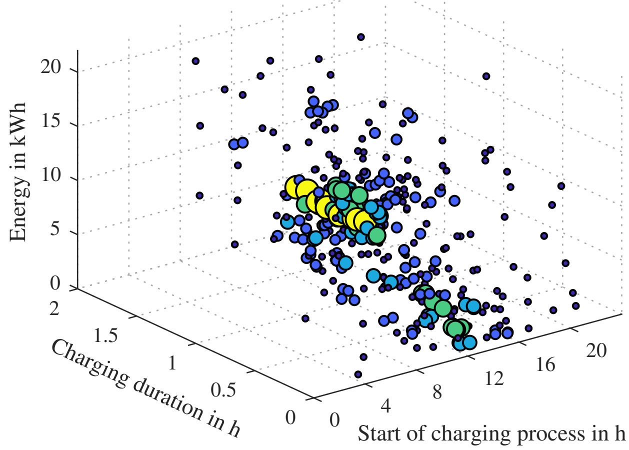


Fig. 4. Load behavior of the fast charging post

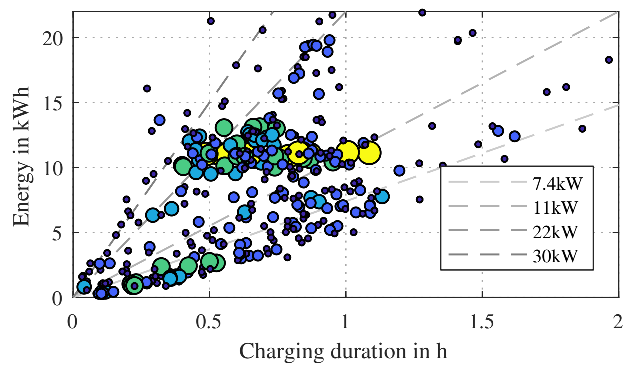


Fig. 5. Charging power of the fast charging post

charges of the eUp and eGolf. Two main factors, namely the start temperature and the start SOC, are used as separators. In order to highlight the influences of the EVs' battery temperature on the charging process, a classification based on the range of temperatures for winter, spring and summer months, provided by a temperature sensor included in the MSG, has been made. The three ranges can be classified in different categories based on figure 3 and are shown in Table II. Each conducted charging process is assigned based on the battery temperature when a connection to the charger is established. A relatively even distribution of start temperatures, shown in Figure 6, supports this separation, as there is sufficient data for each range. Another point is that all accomplished charges are covered and can be classified into one category. This proceeding does not only cover the different seasons due to the alternating ambient temperatures, it also reflects the previous usage of the EV. That is because the influence of previous usage concerning the charge is mainly expressed in a change of the start battery temperature. Furthermore, the same proceeding is used for the start SOC. Based on the distribution of the start SOC in Figure 6 a separation for charges below 35% and above is accomplished.

The third viewpoint is used to specify the parameters of the first two. For the temperature, influencing relations for the development during the charge need to be shown, as it completes the previous analysis. Moreover, the characteristics of the charging profile for the EV plays an important part, which is shown with the development of voltage and current. As cos φ can be considered an electric indicator to show the grid load of inductive or capacitive reactive power, its development is presented for the fast charging station.

IV. Analysis

The explained proceeding was realized using Matlab for the data preparation, analysis and visualization. As continuous data was recorded, it had to be separated into the different charges and each charge had to be connected to the EV model. Additionally, a combination of the recordings of the different data loggers and a cleansing of deviant data was created. In the following sections, subsequent to the mentioned preparation processes, the analysis' outcome of each aspect of the charging process will be dealt with as explained in III-B.

TABLE II
CLASSIFIED TEMPERATURE RANGES

Classification	Winter	Spring/Autum	Summer
Temperature range [°C]	below 5	5 to 20	over 20

A. Viewpoint: Fast charging station

To provide an overview of the entirety of charges performed in this study, figure 4 is presented. As a multidimensional plot it is suitable to show the characteristics of the data and the distribution of the charges all in one graphic. As it is the nature of a scatter plot, each charge is displayed with one point. The affiliating parameters are the charging duration, the start time of the charging process and the energy transferred to the vehicle during the charge. Furthermore, the size and brightness of the orbs is increased with the number of charges with similar characteristics. Most charges tend to be completed before one hour of charging and have a moderate average charging power as it is illustrated in figure 5. Most of the EVs are charged up to an SOC of over 90% and since the charging power drastically drops for the high SOC levels, this results in a considerably lower average power (see IV-B). Subsequently, most observed EVs are not able to continuously receive the high power of

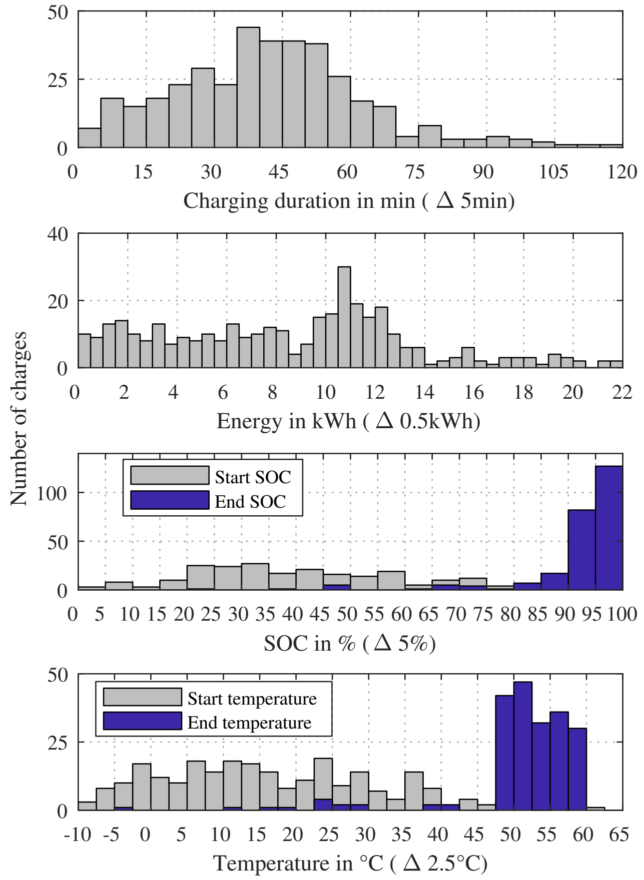


Fig. 6. Number of charges in the data set distributed by the charging duration, energy, start/end SOC and start/end battery temperature

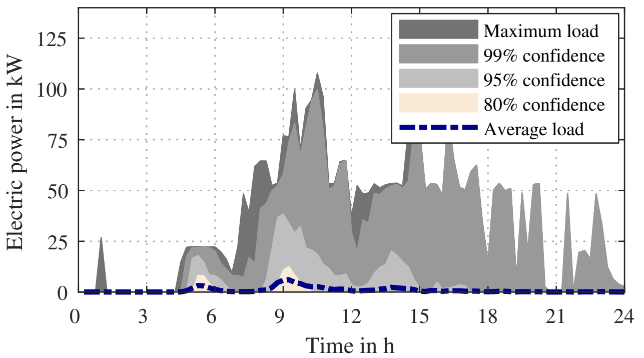


Fig. 7. Load profile of the Fraunhofer fast charging station

22kW defined as the fast charging process. The dashed lines represent the typical charging power classifications given by current standards (see II). The occurrence of charges is further detailed in the density distributions given in figure 6. It is controversial if it is sensible to connect vehicles to the fast charging station, regardless of the momentary SOC and charge them up to full battery capacity. This results in a relatively even distribution of the loaded energy. Another point is that the distribution of the start battery temperature supports the chosen classification for the different seasons in the next section. At the same time, the sharp rise of battery temperatures up to a constant end level expresses the need for a separate consideration in section IV-C.

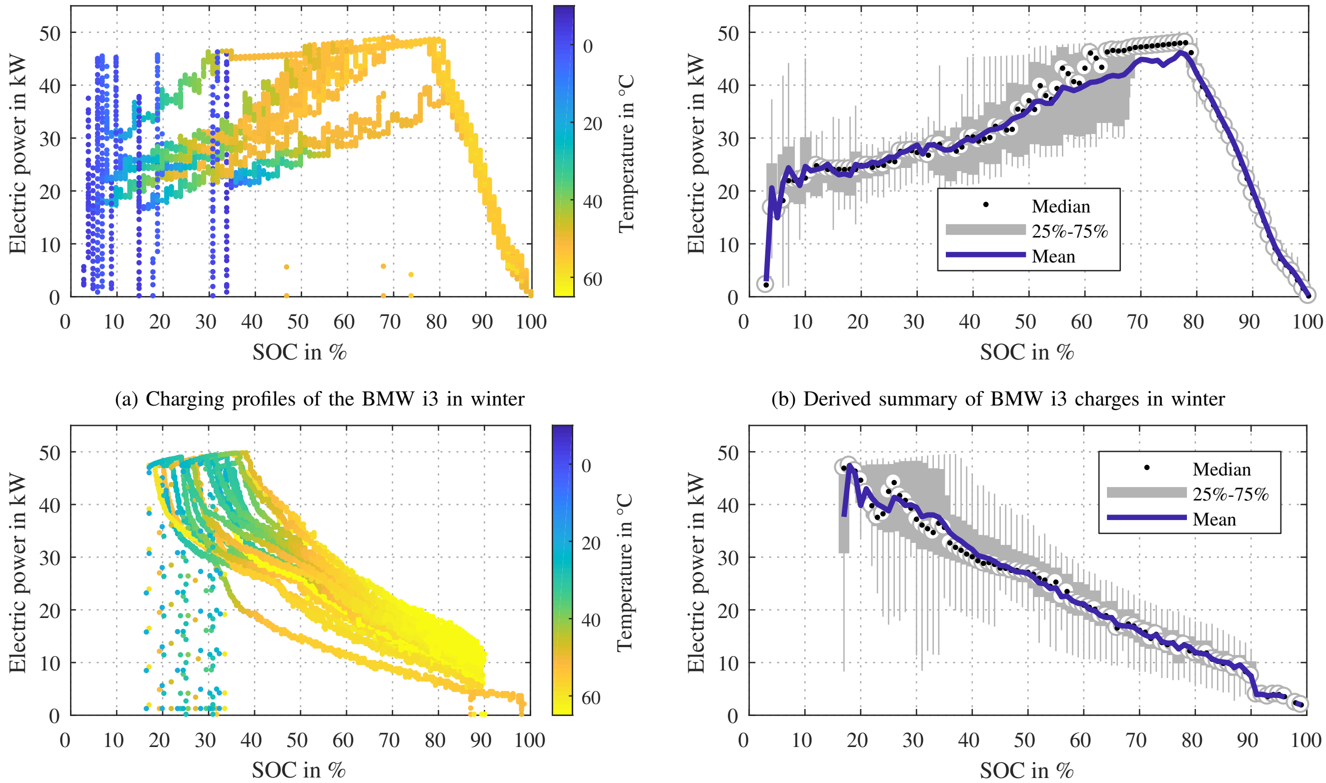
Resulting from the high power of fast charging processes, a peak load of over 100kW due to multiple charges was drawn from the MSG and grid, what is illustrated in figure 7. These high loads contrast the relatively low average load, that takes the usage and idle time likewise into account. This contrast of the temporary peaks during the charge and the relatively low total energy consumption (represented by the area under the average load) supports the observations made in section II, that the actual challenge for the grid from EV charging is about the peak loads and not the additional energy need. The difference is further visualized by the confidence intervals displayed in varying color shades. This shows the potential for intelligent charging systems, that could enable a load distribution over the day: That is a peak flattening effect and a less rugged load profile. Moreover, based on the usage behavior for the single fast charging infrastructure, an individual load limit can be considered. For the observed charging pole, a power of 50kW would suffice over 95% of the daytime.

B. *Viewpoint: Electric Vehicles*

As the previous section only gives an insight into the charging station in general, in this section the single EV charges are taken into consideration. For the observation of the load behavior of the different EV models, each charge was classified in one of the three temperature range categories and one of the two SOC ranges, resulting in six clusters of charging processes for every EV model. Then all charges for each cluster were visualized in a diagram with the associated battery temperature as it is exemplarily displayed in figure 8a and 8c. This in itself provides a great summary of the charging profile, but for a better comparative proceeding each diagram was further processed to a stage seen in figure 8b and 8d. The grey area shows the confidence intervals of the boxplot and the whiskers represent the remaining outside data points. The distribution is further shown by the median points and the mean of all charges. To represent the average charging process, the median is better suited as it ignores single extremas. To actually compare the seasonal changes and the EV models, all medians were visualized in the matrix plot given in figure 9.

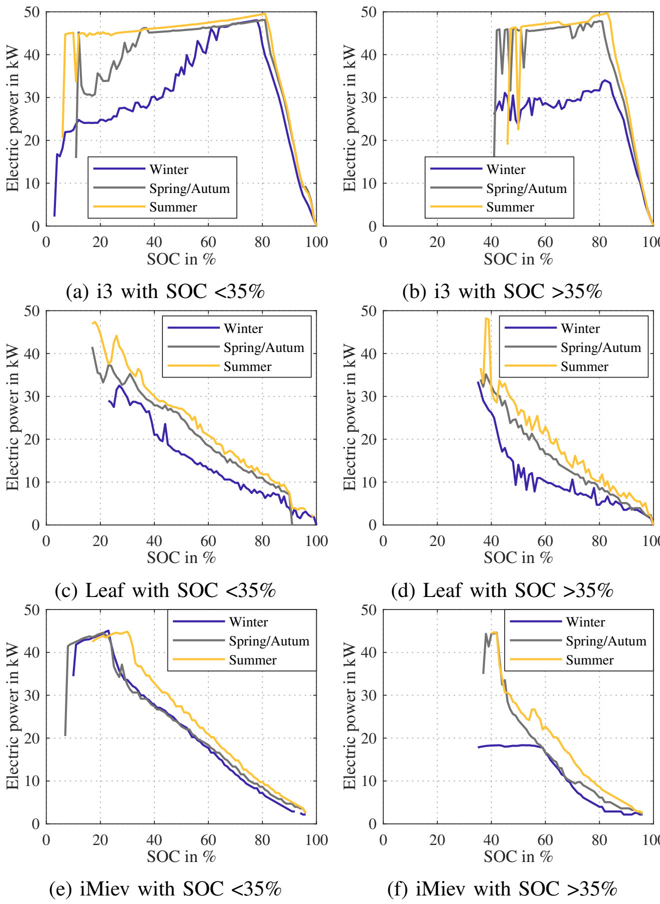
For both SOC ranges, the i3 is able to achieve a charging power of 50kW following the claimed maximum. Especially for temperatures over 5°C the battery immediately accepts a power of 45kW irrespective of the start SOC (see figure 9a and 9b). The charging rate is then slowly increased to the maximum, that is reached around 80% SOC. For temperatures below 5°C charging power is increased from 20kW and is not always able to achieve the same rate as with higher temperatures. This results from a modern battery management system, that regulates the charging rate according to the battery temperature. Particularly for the high start SOC in winter, the EV is not able to ramp up the power in the charging time like for the lower range.

Nevertheless the i3 performs well compared to the 5 year older Nissan Leaf. A clear progression in the charging and battery technology can be noticed, as the i3 is able to keep a high charging rate over a broad range of the SOC whereas the Leaf continuously decreases the power from the start value of the maximum 44kW (see figure 9c and 9d). There



(a) Charging profiles of the BMW i3 in winter
(b) Derived summary of BMW i3 charges in winter
(c) Charging profiles of the Nissan Leaf in Summer
(d) Derived summary of Nissan Leaf charges in summer

Fig. 8. Recorded data for charges with a start SOC below 35% and their derived summary through boxplot, mean and average



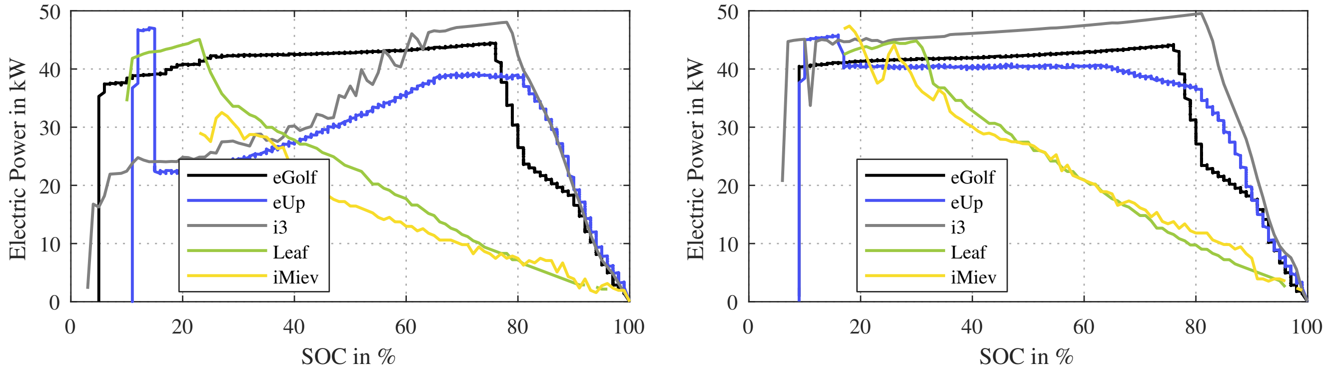
(a) i3 with SOC <35%
(b) i3 with SOC >35%
(c) Leaf with SOC <35%
(d) Leaf with SOC >35%
(e) iMiev with SOC <35%
(f) iMiev with SOC >35%

Fig. 9. The seasonal differences of the charging power

is no range with a constant charging power, consequently this explains the low average charge rating observed in figure 5. Another effect of the temperature can be noted: With a higher start temperature the Leaf is able to receive a noticeably higher power rate throughout the entire charging session. This is particularly notable in winter with a high start SOC, whereby the power rapidly drops into the power ranges of non-fast charging modes 1 and 2 (see figure 9d).

In contrast, the Mitsubishi iMiev, released in 2010, is able to hold the charging power on the highest level of around 44kW for approximatly the defined lower SOC range, with a better performance with the summer temperatures (see figure 9e and 9f). Yet the charging rate rapidly drops after 35% SOC and continuously decreases till the endpoint of the session. Although there is no significant difference for charging with low temperatures when the start SOC is in the lower range, in winter the charging performance of the iMiev with higher SOCs does not surpass 20kW.

Generally speaking, significantly lower charging powers can be expected in winter, as well as a seasonal rise of the power consumption accompanying the increasing ambient temperatures. A progression of EV technology can also be seen, as the i3 is able to almost continuously charge with higher power, especially in higher ambient temperatures. This can be underlined by a comparison to the EVs eUp and eGolf presented in figure 10. The two additional CCS vehicles perform a similar charge to the i3, contrasting the sharply decreasing profile of the older CHAdeMO vehicles. It can be expected that future fast charging procedures are going to make use of the full charging power specified in



(a) Winter charging

(b) Summer charging

Fig. 10. Comparison of the charging profiles of all observed vehicles in the winter and summer

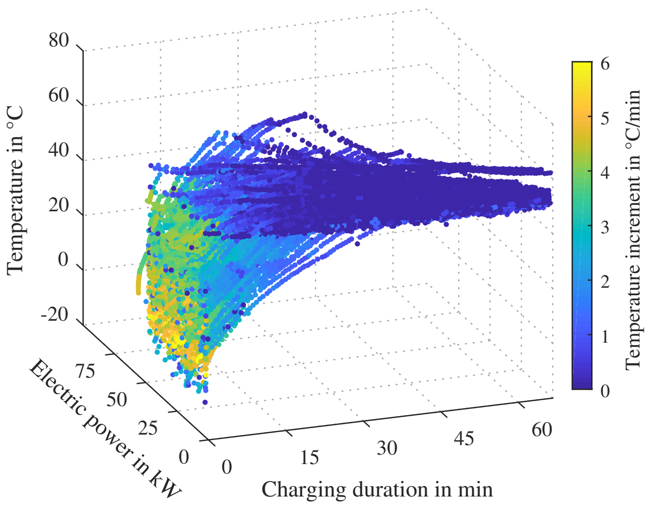


Fig. 11. Rise of battery temperature during a charge, differentiated by power

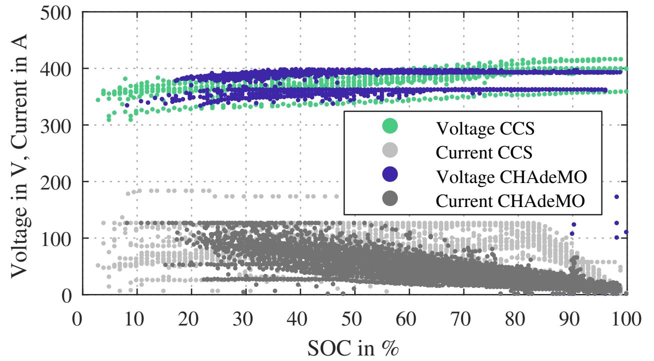


Fig. 12. Development of voltage and current over the course of charging

the respective standards with a battery technology able to receive the power over major parts of the SOC.

C. Viewpoint: Aspects of the Charging Process

For the third viewpoint the relation of the battery temperatures and their rise during the charge are shown in figure 11. It can be noticed that all vehicles are able to maintain a constant battery temperature during the charge irrespective of the momentary charging power. The temperature incremented for one minute is given with the colorscale of the orbs. The momentary rise of the battery temperature peaks at the beginning of the charge and then declines moderately with the rise of the temperature value up to the end level. Especially for start temperatures below 0°C a high increment can be observed. In around 20 minutes, most EVs have reached the maximum temperature of approximately 50°C. This is necessary, as shown previously, to enable the reception of the full charging power in the battery irrespective of the ambient temperature.

Another aspect is given in figure 12 with the course of voltage and current during the charge, respectively the chosen charging profile. For the CHAdeMO vehicles a constant voltage of between 350 to 400V is used, whereas the i3, charging through CCS, slightly increases the voltage during the course of the charge. Nonetheless it can be concluded, that the observed charging post makes use of the charging method "constant voltage (CV)" for all vehicles. The momentary charging power is controlled by the course of current pictured in the lower part of the figure. The same charging profiles as shown previously are combined in this one plot. A limit of the current with 125A based on the maximum charging power of the EV is clearly visible. This composition of the load may vary between chargers and charging methods, but provides a start for more grid load simulations.

The last aspect was chosen to show the additional grid load due to the reactive power that is caused during the fast charging process. Figure 13 provides an overview of all charges with the resulting apparent and reactive power. Moreover the power factor can be calculated with the ratio of active power to apparent power and is displayed with the colorscale for the apparent power. The charging infrastructure overstrains the energy grid with a constant reactive power irrespective of the momentary apparent power or the SOC. There is no correlation to neither the higher reactive loads of up to 20kvar nor the lower values of around 10kvar with the vehicles or ambient temperatures, as the reactive power results from the internal circuit design of the manufacturer. With the apparent power decreasing over the course of charging, a sharp increase of the $\cos\varphi$ in the end of the charge is the consequence. However, the type of reactive power is capacitive, thus a reactive power compensation can be accomplished with inductive EV charging stations.

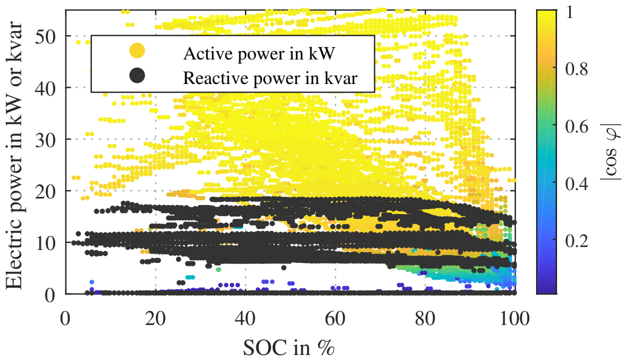


Fig. 13. Development of $\cos\varphi$, apparent and reactive power over the course of charging

Nonetheless, the huge additional loads implied on the grid need to be considered when planning EV infrastructure.

V. Conclusion

In the past years electromobility as a wholesome alternative to established mobility schemata has been increasingly featured and is moving more and more into the perception of an ever-widening public. Therefore, fast charging must be considered a key factor to enable the development of EVs from the current deployment to a mass market adoption. It can be concluded that fast charging imposes a huge burden on the energy grid due to the high peak loads, which is the main challenge for the widening EV fast charging implementation. The insights of this paper create a basis for further research on reactive measurements to shape EV technologies and infrastructure. Each EV model features a distinct charging profile, whereby a progression with the charging and battery technology can be derivated. A strong difference in winter and summer charging was shown with a decrease of charging power in winter. On a national level these seasonal differences will result in a scaled seasonal demand variation. Additionally, the highest increment in battery temperature rise was found to occur in the beginning of the charge with peak values in the negative Celsius range. The utilized charger uses a constant voltage charging profile and burdens the energy grid with a constant reactive power. Additional research and simulations can make use of the presented detailed information about fast charging processes of different EV models to realize more accurate representations of the EV load. The basis of this paper opens up the possibility for further simulations regarding the seasonal change of the EV load on a national level with regard to the different characteristics of EV models.

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References

[1] IEA - International Energy Agency, "Technology Roadmap: Electric and plug-in hybrid electric vehicles: Updated June 2011," 2011. [Online]. Available: www.iea.org/publications/freepublications/publication/EV_PHEV_Roadmap.pdf

[2] ——, "Global EV Outlook 2017," 2017. [Online]. Available: www.iea.org/publications/freepublications/publication/global-ev-outlook-2017.html

[3] H. Wallentowitz, A. Freialdenhoven, and I. Olschewski, *Strategien zur Elektrifizierung des Antriebstranges: Technologien, Märkte und Implikationen*. Wiesbaden: Vieweg+Teubner Verlag / GWV Fachverlage GmbH, 2010.

[4] T. Anegawa, "Characteristics of CHAdeMO Quick Charging System," *World Electric Vehicle Journal*, vol. 4, pp. 818–822, 2010.

[5] L. Christensen, A. V. Nørrelund, and A. Olsen, "Travel behaviour of potential Electric Vehicle drivers. The need for changing: A contribution to the Edison project," *European Transport Conference 2011*, 2011.

[6] C. Weiller, "Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States," *Energy Policy*, vol. 39, no. 6, pp. 3766–3778, 2011.

[7] K. Yunus, H. Z. D. La Parra, and M. Reza, "Distribution grid impact of Plug-In Electric Vehicles charging at fast charging stations using stochastic charging model," *Proceedings of the 2011 14th European Conference on Power Electronics and Applications*, 2011.

[8] GreenGear, "Liste der Elektroautos im Jahr 2017," 2017. [Online]. Available: www.greengear.de/vergleich-uebersicht-elektroautos-eautos/

[9] DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE, "Electric vehicle conductive charging system - Part 1: General requirements (IEC 61851-1:2010); German version EN 61851-1:2011," Berlin, 2012-01-01.

[10] J. Schäuble, S. Balaban, P. Krasselt, P. Jochem, M. Özkan, F. Schellhas-Mende, W. Fichtner, T. Leibfried, and O. Raabe, *Vergleichsstudie von Systemansätzen für das Schnellladen von Elektrofahrzeugen*. Karlsruhe: Karlsruher Institut für Technologie (KIT), 2016.

[11] D. Sbordone, I. Bertini, B. Di Pietra, M. C. Falvo, A. Genovese, and L. Martirano, "EV fast charging stations and energy storage technologies: A real implementation in the smart micro grid paradigm," *Electric Power Systems Research*, vol. 120, pp. 96–108, 2015.

[12] DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE, "Der Technische Leitfaden: Ladeinfrastruktur Elektromobilität," Frankfurt am Main.

[13] Europäische Union, "Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure: 2014/94/EU," pp. 1–20, 2014-10-22. [Online]. Available: http://eur-lex.europa.eu/legal-content/DE/TXT/?uri=CELEX%3A32014L0094

[14] C. H. Dharmakeerthi, N. Mithulananthan, and T. K. Saha, Eds., *Modeling and planning of EV fast charging station in power grid: 2012 IEEE Power and Energy Society General Meeting*, 2012.

[15] J. Wenig, M. Sodenkamp, and T. Staake, "Data-Based Assessment of Plug-in Electric Vehicle Driving," in *Energy Informatics*, S. Gottwalt, L. König, and H. Schmeck, Eds. Cham: Springer International Publishing, 2015, pp. 115–126.

[16] O. Veneri, Ed., *Technologies and applications for smart charging of electric and plug-in hybrid vehicles*. Cham: Springer, 2017.

[17] H. Triebke, G. Göhler, and S. Wagner, "Data analysis of PEV charging events in rural and business environments: a load behaviour comparison," 2015.

[18] S. Wagner, G. Göhler, H. Triebke, F. Klausmann, R. Lange, S. Schmidt, and F. Edel, "PEV-charging in rural and business environments. A user behaviour and demand comparison: Presented at the Conference on Future Automotive Technology, CoFAT 2016, Focus Electromobility," Fürstenfeld, 03. - 04. Mai 2016.

[19] N. Hartmann and E. D. Özdemir, "Impact of different utilization scenarios of electric vehicles on the German grid in 2030," *Journal of Power Sources*, vol. 196, no. 4, pp. 2311–2318, 2011.

[20] Schnellladenetz für Achsen und Metropolen, "Projektinhalte," 2017. [Online]. Available: http://www.slam-projekt.de/projektinhalte.php

[21] Kraftfahrt-Bundesamt, "Neuzulassungen von Personenkraftwagen nach Marken und Modellreihen im Mai 2017," Flensburg, 2017. [Online]. Available: www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2017_monatlich/FZ10/fz10_2017_05_xls.xls?__blob=publicationFile&v=4

[22] R. Schutt and C. O'Neil, *Doing Data Science*. Sebastopol, CA: O'Reilly Media, 2014.