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Fast charging stations with stationary batteries

- An techno-economic comparison of fast charging at highways and in cities -

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Abstract

Fast charging infrastructure is widely acknowledged as necessary for the market success of electric vehicles. However, fast charging requires cost intensive infrastructure and grid connections. Accordingly, the risk of sunk cost is high, although fast charging infrastructure might be profitable in the medium to long term. In addition, the demand for fast charging varies greatly and the maximum power of charging stations might only be needed for a short time period per week. Although the profitability of stationary storages and the demand for fast charging have gained broad attention in literature, the specific question, how and under which circumstances stationary batteries can increase the profitability of fast charging stations has not yet been addressed for all potential applications. Here, we analyze the extent to which stationary storages can increase the profitability of fast charging stations by reduced grid connection costs on the one hand and additional revenues from intraday trading of electricity on the other hand. We compare different battery technologies and distinguish two use cases: fast charging in cities and at highways. Our results indicate that the profitability of a stationary storage installed together with a fast charging station depends on various parameters. While for a city fast charging station, intraday trading might lead to lower cost, this is not the case for highway stations since the heavy use motivated by intraday trading may reduce battery lifetime considerably. Our results underline the importance of second life batteries since low-cost batteries have a significant impact on the system's profitability.

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Keywords: BEV; fast charging; stationary battery; techno-economic analysis; grid connection

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1. Introduction

Charging infrastructure for electric vehicles (EV) is an important instrument to address the barrier of the limited battery range of EV (Egbue and Long, 2012). Compared to charging options with power levels below 22 kW (see e.g. Funke et al., 2015), fast charging with high charging power is the favorable option for long distance trips (Neaimeh at al., 2017) and is the only charging option that may be operated profitably in the medium term (Funke et al., 2016; Jochem et al., 2016a).

However, fast charging stations face the challenge of high grid connection cost due to high (peak) power demand. For example, a fast charging station with four charging points of 130 kW charging power already requires a grid connection of more than 0.5 MW, which (together with the conventional load) exceeds the power limit of many conventional distribution grid transformers. These challenges grow when the workload of fast charging stations increases, which may occur when market uptake of EV continues and fast charging stations are allocated in an optimal way (i.e. as few as possible locations with high workloads as indicated by Reuter-Oppermann et al., 2017). This would put significant stress on the local electricity grid.

The demand for fast charging events fluctuates heavily both during the day and between days (Neaimeh et al., 2017; Jochem et al., 2016b; see also Section 3.2). Consequently, the fast charging station operates at peak power only for a limited amount of time. Thus, adding stationary storage systems might increase the profitability of fast charging stations in two ways. First, it might decrease grid connection cost, as peak power demand at the charging station could partly be provided by the stationary storage. Second, the stationary storage could be used to provide grid services or participate in different electricity markets.

Finally, two different use cases of fast charging stations can be distinguished. The first is fast charging stations at highways for long distance trips, as described above. The number of minimal required charging sites along the highway might be comparable to today´s highway fuel stations. This would lead to high workloads for each single location. For the minimum amount of 97 charging sites for the German highway system, an average size of about 100 charging points per site in 2030 seems reasonable (Reuter-Oppermann et al., 2017). The second use case is fast charging stations in cities that might be used as an alternative to overnight home charging by vehicle drivers without private charging options. While fast charging at highways has already been analyzed and quantified in literature (cf. Jochem et al., 2016a; Gnann et al., 2018), fast charging needs in cities are still widely debated.

1.1. Literature review and scope of this study

Evaluating the cost-efficiency of a stationary storage for fast-charging stations comprises two main aspects. First, a technically effective operation has to be determined and second, the profitability of the stationary storage operation has to be evaluated. However, studies analyzing fast-charging stationary storages often focus on only one of these two aspects (Table 1). One part of studies focuses on the technical analysis of stationary storage systems, but does not take the profitability of the stationary storage into account. García-Triviño et al. (2017) for example analyze the technical feasibility of a fast charger operation with a solar PV-system (photovoltaics) in combination with a stationary storage and a limited grid connection. Analogously, various studies have analyzed the technical implementation of a stationary storage into micro grids (Sbordone et al., 2014; Gjelaj et al., 2017a). Other studies in contrast focus on economic aspects of stationary storages but do not take individual charger or stationary storage operation into account. The aim of these studies often is to show the general techno-economic feasibility of stationary storages under certain circumstances (e.g. Gjelaj et al. 2017b; Chaudhari et al., 2016).

The combination of a technical and economic analysis of a fast charging station has been performed only to some extent. Bayram et al. (2012) e.g. analyze how a stationary storage might affect blocking probability (i.e. situations in which the station has to reject new arrivals) of a fast charging station for different arrival rates of EV. They analyze the influence of battery power and capacity on charging station profitability. Although they focus their analysis on EV not rejected, they do not analyze other purposes such as peak shaving or especially intraday trading. Accordingly, Richard and Petit (2018) systematically analyze a stationary storage for a charging station with 120 kW total power for three outlets. The analysis comprises the technical operation for a daily charging schedule as well as its economic analysis. In contrast to the present study, the authors do not take into account daily patterns or different battery technologies. Similarly, Cunha et al. (2016) focus only on a redox-flow battery as a stationary storage. In another study, Kucevic et al. (2018), techno-economically assess the operation of a stationary storage both for a highway charging station and a bus depot charger. In their detailed analysis, the authors focus the operation of the storage to avoid grid reinforcement cost.

Finally, the analyzed studies often focus on peak load reduction but the question of how intraday trading might affect profitability and operation of a fast charging stationary storage is seldom part of the analyses. Hesse et al. (2017) is the only relevant study that analysis intraday trading in our research context. The authors review a broad part of the stationary system design by discussion e.g. battery technology, grid connection, operation purposes and profitability. However, although the authors discuss the modelling of stationary storages based on literature findings, they do not model stationary storage operation themselves and thus are not able to quantify the benefit of intraday trading.

Table 1. Literature overview on fast-charging with stationary storages.

	Technical	*TCO*	*Load curve*	*Battery sizing*	*Operation purpose*		
					Peak shave	intraday	other
Bayram et al., 2012	Yes	Yes	Yes	Yes	No	No	Yes
Richard & Petit, 2018	Yes	Yes	Yes	Yes	No	No	Yes
Salapić et al., 2018	Yes	Yes	Yes	Yes	Yes	No	No
Kucevic et al., 2017	Yes	Yes	Yes	No	No	No	Yes
Cunha et al., 2016	Yes	Yes	No	No	Yes	No	No
Gohla-Neudecker et al., 2017	Yes	Yes	-	Yes	Yes	No	Yes
García-Triviño et al., 2016	Yes	No	Yes	No	No	No	Yes
Sbordone et al., 2015	Yes	No	Yes	No	Yes	No	No
Gjelaj et al., 2017a	Yes	No	Yes	Yes	Yes	No	Yes
Deng et al., 2015	Yes	No	No	No	No	No	Yes
Negarestani et al., 2016	Yes	No	Yes	Yes	No	No	Yes
Chaudhari & Ukil, 2016	No	Yes	Yes	No	No	No	Yes
Yang & Ribberink, 2018	No	Yes	Yes	Yes	Yes	No	Yes
Gjelaj et al., 2017b	No	Yes	No	Yes	Yes	No	No

Altogether, as summarized in Table 1, studies on stationary storages for fast charging stations often focus on specific aspects. Thus, a techno-economic evaluation of such a stationary storage system that also takes the possibility of intraday trading into account has not or not sufficiently been addressed in literature.

1.2. Structure of the paper

The aim of this paper is to contribute to this field of research in three aspects. First, this contribution provides a general comparison of fast charging stations in cities and along highways (cf. Section 2). This comparison focuses on aspects that are relevant for the grid connection to underline the different requirements. Second, we develop an optimization model that calculates the operation schedule of a stationary battery with a predetermined size used both for cutting the peak load induced by the EV demand and for participating in the intraday electricity market. We apply this model to the different use cases. Third, we perform an economic analysis on the profitability of stationary storages for three different use cases: two in cities and one along the highway (cf. Section 3). In our calculations, we assume a mature market corresponding to 6 million EV in Germany (about 15% market share) in 2030.

2. Fast charging in cities and along highways

2.1. General comparison

Fast charging both in cities and along highways needs high power above 50 kW per outlet to be able to charge the vehicles within a limited amount of time for user convenience. This leads to significant grid connection requirements, especially when compared to slow charging options. However, a differentiation between fast charging along highways and in cities is necessary since charging behavior at the different sites differs significantly for multiple reasons (see also Table 2).

First, we identify two different use cases. Fast charging along the highway network enables long distance trips (interim charging). For most of private driving, long distance trips are rare and thus fast charging along the highway network is a rather exceptional case for an average private car driver (Weiss et al., 2014). Thus, the usage pattern of this type of charging infrastructure depends on the temporal and geographic distribution of long distance trips. This has already gained broad attention and thus, is well understood (Jochem et al., 2016b; Gnann et al., 2018; Weiss et al., 2014; Funke and Plötz, 2017). By contrast, fast charging in cities might replace overnight charging for car drivers with no home or work place charging. These fast charging events would be needed regularly. Early adopters of EV are characterized by a high availability of overnight charging (Plötz et al., 2014), and today´s charging behavior of EV drivers (cf. Neaimeh et al., 2017) has to be interpreted against this background.

Second, the two types of charging infrastructure differ regarding station size and charging power, resulting from the different use cases. Fast charging stops along the highway network are characterized by high time restrictions. Drivers mostly stop because they need to recharge, similar to today´s fuel stops. Hence, the charging power of the charging stations is decisive to minimize charging times. This is underlined by current efforts to increase charging power even up to 350 kW (Ionity, 2017), which would lead to charging times of less than five minutes for 100 km. Since infrastructure would have to be developed for every charging site along the highway, the number of sites should be limited to a minimum in order to limit the aggregate expenditures from a macroeconomic perspective. Accordingly, large sites with a high number of charging points are needed (in the long-term). In contrast, EV drivers in cities might use the charging time for other activities, such as running smaller errands. This alleviates time pressure and thereby the necessity for high charging power. As these sites could be placed at supermarket parking lots (Gnann et al., 2017a), where space is limited, a smaller number of outlets per site, but a larger number of sites would be needed for city fast charging, compared to fast charging along highways.

Fast charging stations along the highway could thus have a peak power demand of well above 1 MW which makes the necessary grid connection costly. However, for fast charging in cities, peak power demand is within the range of transformer stations often used in German urban areas (400 kVA or 630 kVA, Fraunholz, 2017). At larger supermarkets that have their own transformer station, even the use of existing power capacities could be sufficient for smaller charging sites. Instead of expanding the existing grid connection to allow for a higher peak charging load, a stationary storage might be rational.

Table 2. Outline of fast charging in cities and along highways.

Parameter	Fast charging in cities	Fast charging at highways
Use case	Opportunity charging as alternative to overnight charging	Interim charging
Charging power per outlet	~50 kW	>120 kW
Availability of space	Limited	High
Station size	2-8 outlets	> 8 outlets
Maximum power demand per site	200 - 400 kW	> 1 MW
Grid connection	Potential to use existing capacities on medium-voltage level	New connection to high-voltage grid
Potential benefits from storage	Reducing peak power demand; Load shifting; Arbitrage	Reducing peak power demand; Load shifting; Arbitrage

The benefits resulting from the battery storage depend on the load patterns of the two use cases. While the resulting load pattern for highway charging is characterized by a pronounced peak power demand on one day (Friday afternoon), the load pattern for inner-city charging is more regular and less peaked. For a detailed description of the load patterns, please refer to Section 3.

2.2. Definition of use cases

In this work, we analyze, if stationary batteries increase the profitability of fast charging stations. We carry out the calculations for the year 2030 and define three exemplary use cases:

Case 1a: a city charging site with a total maximum charging power of 200 kW and an available grid connection of 100 kW. Maximum charging power per charging point is 50 kW.
Case 1b: a city charging site with a maximum charging power of 200 kW and an available grid connection of 150 kW. Maximum charging power per charging point is 50 kW.
Case 2: a highway charging station with a maximum of 10 MW charging power and a grid connection of 8 MW. Maximum charging power per charging point is 100 kW.

As described in Section 2, fast charging within cities might substitute or even be supplementary to home or workplace charging. One promising and evident siting of these charging stations is in the semi-public space on supermarket parking lots. A corresponding development can already be observed in Germany: currently, supermarket chains provide about 10% of all fast charging sites in Germany to their customers during their purchase (own analysis based on official data from the Federal Network Agency (BNetzA, 2019)). Other suitable siting options are e.g. public car parks that allow to charge also outside supermarket opening hours. For this use case, we assume the charging operator to being able to use existing free power capacities of the transformer connection for charging. The battery covers the remaining power required for satisfying EV peak demand. To analyze the implications of locally different free power capacities on stationary storage profitability, we analyze the two above-mentioned cases. Fast-charging stations at supermarkets might be an important option to reach electric vehicle users beyond the current early adopters with no home or other regular charging option (cf. Wietschel et al., 2015).

In contrast, a highway charging station provides fast charging to enable long distance trips, analogous to highway fuel stations. Here, we analyze a highway charging station at a busy motorway with a high demand for fast-charging events (cf. Jochem et al., 2016b). For such a highway station, a new grid connection to the medium-voltage grid is necessary. Finally, our approach accounts for the development towards increasing EV battery capacities and charging power of fast chargers along highway corridors that might lead to fewer charging sites but with higher maximum power.

3. Data

3.1. EV load profiles

To determine the charging load curve at a city charging station (with 50 kW maximum charging power per outlet), we use the model ALADIN which is described in detail in (Gnann, 2015). Based on vehicle driving profiles (all trips within one week), the vehicle buying decision are modelled and for EV usage, charging at home, work and public charging points are simulated. The charging infrastructure is set up based on the users' demand for it. For interim charging at highways, trips have to be interrupted which is not considered in the ALADIN model. Here, a user only charges in public if her battery state of charge is below 50% and there is a free charging point or if she has no home charging option available. The data used in ALADIN stems from (Hautzinger et al., 2013), a household travel survey for the region of Stuttgart that was transferred to all households in the region.

All modifications and preparations to work for the ALADIN model have been comprehensively described in (Gnann, 2015). The very detailed simulation permits an analysis of the charge load for all charging points within a geographical granularity of 100x100 m² in the inner city of Stuttgart. In this analysis, we normalize the power of a charging station to 200 kW which would result in approx. 70 charging stations for the region of Stuttgart. Accordingly, a charging station could be reached within 10 min. The resulting charge load curve is shown in Fig 1. The charging demand in cities shows pronounced peaks on every day. From Monday to Thursday, charging demand is largest in the evening, reaching a charging load of 150 kW. On Fridays, the charging peak is highest (up to 200 kW) and peak demand lasts longest. On Saturday, the peak load is below 150 kW during the early afternoon with no pronounced peak, while on Sundays the average load is comparably low but with a pronounced short peak of almost 150 kW.

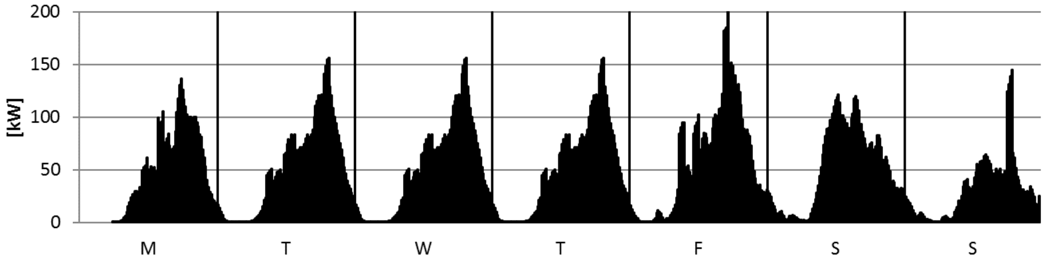

Fig. 1. Charging load curve in cities. Four charging points with a maximum charging power of 50 kW each. Own illustration based on simulations.

Gnann et al. (2017b) show that there is a significant difference in the resulting load curves from charging along the highway compared with those from fast charging hubs in a city. Currently the allocation of fast charging stations along highways is in the focus of governments and we observe severe investments. In literature, several different methods for defining an optimal number of charging stations and their locations were discussed (cf. Jochem et al., 2016). Reuter-Oppermann et al. (2017) compare an optimizing approach with a simple heuristic. The optimizing approach allocates as few fast charging stations as possible along the German highway. The data basis is a European traffic-flow matrix with all numbers of cars driving from an origin O to a destination D. It ensures that a certain percentage of these OD-flows can fulfil their trip assuming an average battery capacity for all EV. Based on these results, the number of charging points at each charging location is defined (Jochem et al., 2016a).

The load pattern from fast charging stations along the highway (Fig 2) has also a pronounced peak on Friday evening and, to a lesser extent, on Saturday evening. However, on weekdays the charging patterns shows, in contrast to the city use case, a double peaked structure and a comparatively high charging demand throughout Saturday afternoon which makes a relatively high grid connection necessary to always meet charging demand.

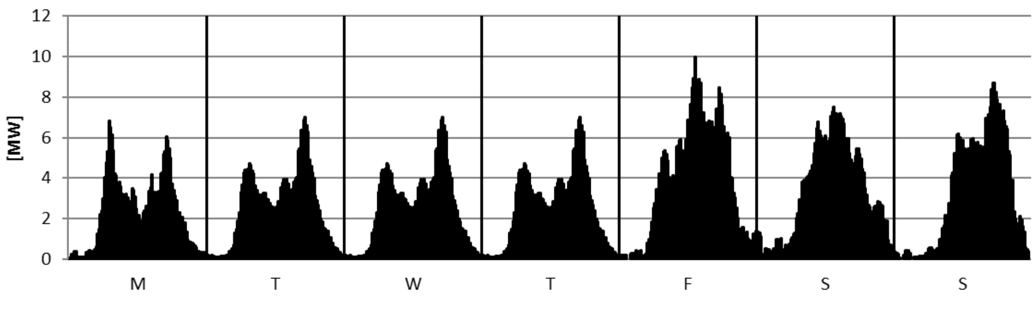

Fig. 2. Charging load curve along highways. Maximum charging power per charging point: 100 kW. Own illustration based on simulations.

3.2. Techno-economic parameters

For the total cost of ownership calculation (see Section 4.1), we use a uniform interest rate of $i = 5\%$ (cf. Serradilla et al., 2017) for all investments. Technology specific data is summarized in the following two paragraphs. To account for the uncertainty of the assumptions, we performed a sensitivity analysis for the interest rate, operating expenditures and storage lifetime (cf. Section 5.5).

3.2.1. Storage systems

For the stationary storage system, we analyze mainly Lead-Acid batteries, Redox-Flow and Li-Ion batteries. We address Second life Li-Ion batteries in a sensitivity analysis. For the calculation, we use parameters as shown in Table 3. The time horizon is 2030 and possible ranges of the parameters are shown in parenthesis.

Table 3. Technical parameters of the analyzed grid storage devices from literature (time horizon 2030).

Parameter	Lead-Acid	Li-Ion	Redox-Flow	Li-Ion second life
Cost [€/kWh]	100 (50-150)	500 (160-600)	300 (115-430)	100 (35-100)
Cost [€/kW]	-	-	600	-
Cycle efficiency	80% (75-80%)	90% (85-95%)	80% (75-80%)	80% (65%-85%)
Cycle life	4.000 (1.000-4.000)	20.000 (2.000-23.000)	13.000 (10.000-13.000)	3.000 (3.000-4.000)
Calendar life	13 (10-15)	23 (10-25)	20 (14-20)	10
Depth of Discharge	50%	90%	100%	80%
Sources	Ralon et al., 2017; GIZ, 2015; Kairies, 2017	Ralon et al., 2017; Kairies, 2017; Marano et al., 2009; Schmidt et al., 2017	Ralon et al., 2017; Kairies, 2017; Reinicke, 2015	Ahmadi et al., 2017; Heymans et al., 2014

In the table we refer to all types of Li-Ion batteries as "Li-Ion" which gives us a wide range of parameter values due to the differences in Li-Ion technology. However, in our analysis we focus on LTO battery chemistry with high cycle and calendar life at comparably high cost.

A potential self-discharge of the battery is neglected in this study since it is limited for Li-Ion and Lead-Acid batteries in a range from two to six percent per month (Kairies, 2017).

Due to lack of robust data, operating expenditures of stationary storages are assumed to comprise 2% of the total investment, a commonly used assumption in economic analyses (cf. Wietschel et al., 2017). The assumed lifetimes T_{St} of the different battery types are summarized in Table 2.

3.2.2. Grid connection cost

For city fast charging stations, we assume that the battery could save grid connection cost of 75,000 € (Fraunholz, 2017). We assume the same cost for both power levels. However, grid connection cost might be even as high as 200,000 € (Fraunholz, 2017), the effect of which is analyzed in the results (Section 4.3).

For the highway station, we assume the battery to save 1 million € for a 2 MW grid connection (Gras, 2016). We address the uncertainty of the grid connection cost factors by analyzing break-even grid connection cost at which a stationary battery starts to economize. According to the depreciation period given in the German electricity network fee ordinance (StromNEV 2005), we assume a lifetime of $T_{GC} = 35$ years for the grid connection components.

3.3. Intraday price data

When not being used for load shifting, the stationary storage is used for trading on the intraday market. For the analysis, we use the 2017 market prices for 15-minutes products from the intraday auction at the European Power Exchange EPEX SPOT (Fig. 3). We neglect any transaction costs related to the trading.

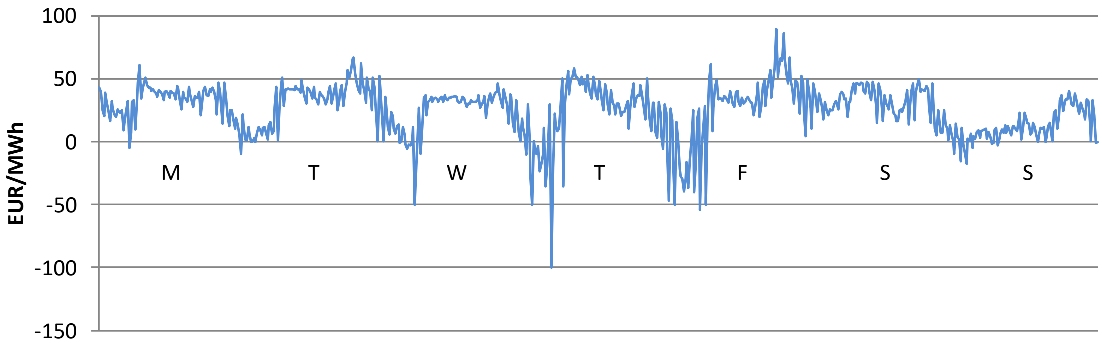

Fig. 3. Intraday prices during calendar week 8, 2017. Own illustration based on EPEX SPOT (2017).

4. Methodical approach

4.1. Battery sizing

We assume the stationary battery to operate in such a way that its first priority is to provide the fast charging station with sufficient energy and power so that the EV demand exceeding the maximum grid connection power can be covered at all times. We calculate the battery dimensions for each use case in two steps. First, the battery power rating is determined as follows:

– The required discharge power and thus power rating P_{Bat} is obtained by subtracting the grid connection power P_{Grid} from the peak EV demand $P_{EV,peak}$. This ensures that every consumption at the fast charging station exceeding the grid connection power can be covered:

$$P_{Bat} = P_{EV,peak} - P_{Grid} \tag{1}$$

Second, the battery capacity is determined:

– The energy necessary for fulfilling the EV demand (available battery capacity) is calculated by selecting the maximum energy consumption $E\_av_{max,EV}$ of all periods blocked for the EV application.

– The depth of discharge (DoD) is considered, determining the nominal battery capacity $E\_nom_{max,EV}$ by increasing the available battery capacity:

$$E\_nom_{max,EV} = E\_av_{max,EV} \cdot \frac{1}{DoD} \tag{2}$$

– In addition, we assume Lead-Acid and Li-Ion batteries to lose 20% of their capacity over their lifetime. As the battery storage has to supply sufficient energy even at its end of life, initial battery capacity is increased by considering the remaining capacity E_{in} at the end of battery life (C_{EOL}):

$$E_{in} = E_{nom_{max,EV}} \cdot \frac{1}{C_{EOL}} \tag{3}$$

– Finally, the nominal battery capacity E_{nom}E_nom is determined as follows, making sure that the battery is operated at a maximum C-rate of 1 at its end of life:

$$E_{nom} = max\{P_{Bat} \cdot (DoD \cdot C_{EOL})^{-1};\ E_{in}\} \tag{4}$$

4.2. Battery operation

In a next step, we model the battery operation for a given battery size. The peak shaving is implemented by blocking certain periods where the battery can only be used for complementing the operation of the fast charging station. Both the EV load curve and the set grid connection power determine the number and length of those periods (cf. Fig. 4). Within the blocked periods, the battery operation is simulated under the assumption of perfect foresight. At the beginning of each peak shaving period, the battery state of charge (SOC) is preset to 100%. The following discharge is determined by the EV demand exceeding the grid connection power. After the last discharge event, the battery is recharged at its maximum power rating. Each period ends as soon as 100% SOC is reached.

Outside the periods blocked for the EV application, the stationary battery is used for arbitrage. We assume that it participates in the German intraday market, where a mixed-integer linear program (MILP) determines its operation. We develop the MILP that maximizes the revenues (r_{ID}) realized by arbitrage and considers both intraday market prices and the constraints imposed by the EV application. The target function looks as follows:

$$max\, r_{ID} = \sum_{t=1}^{T} price_t \cdot (E_t^{sold} - E_t^{purchased}) \tag{5}$$

The intraday market price $price_t$ determines whether energy is sold (E_t^{sold}) to or purchased ($E_t^{\text{purchased}}$) from the intraday market.

Constraint (6) ensures that the energy is balanced at all times, P_t^{charge} being the charged power, $P_t^{\text{discharge}}$ the discharged power, d the duration of one time step.

$$\frac{E_t^{sold}}{d} + P_t^{charge} = \frac{E_t^{purchased}}{d} + P_t^{discharge} \quad \forall t \tag{6}$$

Battery discharge and charge during the periods blocked for the EV application is predetermined and thus enter the model as parameters ($P_t^{charge,fix}$ and $P_t^{\text{discharge},fix}$), resulting in the following formulation for the SOC:

$$SOC_t = SOC_{t-1} + \left[\left(P_t^{charge} + P_t^{charge,fix}\right) \cdot \eta - (P_t^{discharge} + P_t^{discharge,fix}) \cdot \frac{1}{\eta}\right] \cdot d \quad \forall t \tag{7}$$

The model does not consider costs or revenues resulting from the operation within the EV application. Furthermore, costs for operation and maintenance are neglected. We assume that continuous amounts of energy can be traded and no minimum market volumes exist on the intraday market. The model results include revenues and cost due to the arbitrage application, as well as the optimal battery schedule (Fig. 1) and resulting cycles for both use cases, all over the course of a year. We use IBM ILOG CPLEX Optimization Studio as software for the implementation.

4.3. Economic evaluation

We calculate the total cost of ownership (TCO) of a stationary battery TCO_{St} as the sum of capital expenditures c_{capex}, operating expenditures c_{opex} minus potential revenues from intraday trading r_{ID} plus the cost of a lower cycle lifetime of the battery due to intraday trading c_{ID}:

$$TCO_{St} = c_{capex} + C_{opex} - r_{ID} + c_{ID}\mathrm{TCO_{St}} = \mathrm{a_{capex}} + \mathrm{a_{opex}}\text{-}\mathrm{r_{ID}} + \mathrm{c_{ID}} \tag{8}$$

The revenues of intraday trading r_{ID} depend on the battery capacity, the charging load curve and electricity market prices (here: intraday market). Accordingly, we determine r_{ID} in a detailed simulation of battery operation both guaranteeing to meet EV charging demand and taking advantage of intraday market price spreads.

Capital expenditures are calculated as annualized investments of the stationary storage I_{St} minus annualized investments of potential reduced investments in the grid connection ΔI_{GC}:

$$c_{opex} = \frac{(1+i)^{T_{St}\cdot i}}{(1+i)^{T_{St}-i}} \cdot I_{St} - \frac{(1+i)^{T_{GC}\cdot i}}{(1+i)^{T_{GC}-i}} \cdot \Delta I_{GC} \mathrm{a}_{\mathrm{capex}} = \frac{(1+\mathrm{i})^{\mathrm{T_{St}}*\mathrm{i}}}{(1+\mathrm{i})^{\mathrm{T_{St}}\text{-}1}} * \mathrm{I_{St}} - \frac{(1+\mathrm{i})^{\mathrm{T_{GC}}*\mathrm{i}}}{(1+\mathrm{i})^{\mathrm{T_{GC}}\text{-}1}} * \Delta \mathrm{I_{GC}} \quad (9)$$

Accordingly, if TCO are positive, the stationary battery decreases the profitability of the charging station, for negative TCO the stationary battery is beneficial.

5. Results

Our analysis shows, that a Lead-Acid battery might be interesting as a stationary storage for all use cases while the cost-efficiency of the other battery chemistries is mainly influenced by the grid connection cost of the charging station as presented in the following.

5.1. Battery sizing

The power of the different stationary storages results from the grid connection power to be replaced by the battery. The net energy capacity of the different battery types varies due to their different charging efficiencies and depths of discharge, as summarized in Table 3. The battery capacity of the Lead-Acid battery is almost twice the battery capacity of the other two technologies. While at a highway station, the additional space for the Lead-Acid battery might not be important, limited space availability in cities might favor the more efficient Li-Ion battery.

Table 4. Required gross battery capacity for the different use cases.

	Battery power	Lead-Acid	Li-Ion	Redox-Flow
City 100 kW grid connection (case 1a)	100 kW	490 kWh	256 kWh	196 kWh
City 150 kW grid connection (case 1b)	50 kW	125 kWh	70 kWh	50 kWh
Highway (case 2)	2000 kW	5000 kWh	2780 kWh	2000 kWh

5.2. Battery operation

Subsequently, the battery operation is determined based on the selected battery size and EV charging profiles described in Section 3.1. The battery capacity considered in the calculation is set to the available capacity at the end of battery life. The MILP is solved for one year and we assume the subsequent years to show identical battery operation patterns and revenues from arbitrage (intraday trading).

5.2.1. Use case city

The charging load curve of a city fast charging station shows pronounced peaks. Accordingly, the maximum charging (or grid connection power, respectively) of 200 kW is only needed during one 15 min per week (Friday, 17:15-17:30). In addition, more than 150 kW charging demand is also limited to 2:45 hours per week. Due to the recurring pronounced charging peaks on every day, especially the load shift potential of a stationary battery is an important advantage for a city fast charging station. The most pronounced charging peak occurs on Friday, resulting in the longest period during which the stationary battery is blocked for load shifting.

If the grid connection of the city charging station is restricted to 100 kW (use case 1a), this requires one blocked period per day during the evening peak hours. The periods' lengths range between 1.5 hours on Sunday to 10 hours on Friday noon to evening (cf. Fig 4). The resulting revenues amount to 2,532-3,287 €/year, which corresponds to specific yearly revenues between 13-18 €/kWh. The battery is cycled around 1,219-1,498 equivalent full cycles per year.

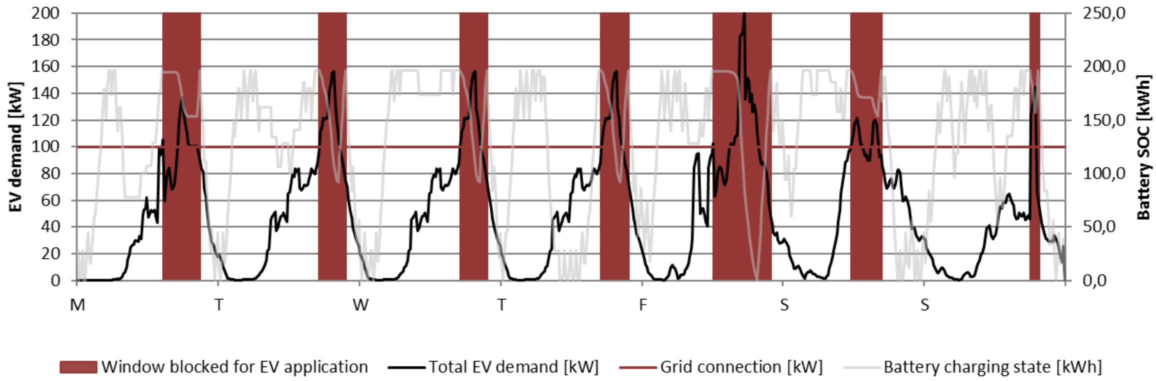

Fig. 4. Charging load curve in cities (black line). Horizontal red line indicates level of grid connection (here: 100 kW). During the red squares, the battery is reserved for load shifting and not available for intraday trading. Grey line: battery SOC. Own illustration.

In case of higher available grid connection power of 150 kW (use case 1b), the periods in which the battery is reserved for serving the EV demand and recharging last between 45 minutes and 2.5 hours (cf. Fig 5). The MILP results show high usage of the battery outside the blocked periods. Compared to use case 1a, there is more time in which the battery can be used for intraday trading. Accordingly, the specific yearly revenues are higher and amount to 28-37 €/kWh. In absolute numbers, this results in yearly revenues from intraday trading of 1,358 € for the Lead-Acid and Redox-Flow batteries, and 1,830 € for the Li-Ion battery due to lower efficiency losses. The frequent battery usage translates into 1,968-2,741 equivalent full cycles per year.

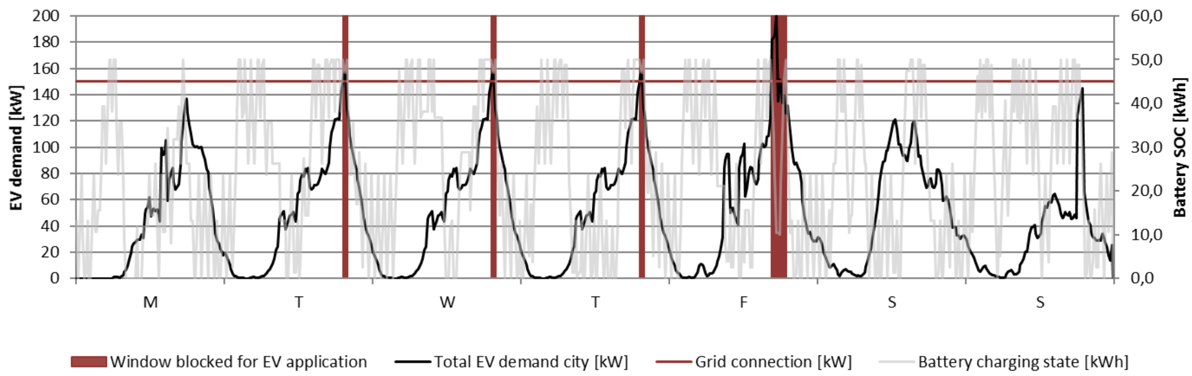

Fig. 5. Charging load curve in cities (black line). Horizontal red line indicates level of grid connection (here: 150 kW). During the red squares, the battery is reserved for load shifting and not available for intraday trading. Grey line: battery SOC. Own illustration.

5.2.2. Highway case

Although the demand pattern of the highway fast charging station (use case 2) differs, a similar peak period can be observed on Friday afternoon. In this use case, the battery is used for load shifting on Friday afternoons for 6 hours and on Sunday evenings for around 2.5 hours (cf. Fig. 6.). The battery operation optimization leads to yearly revenues of 55,827-73,574 €, or 28-37 €/kWh/year. The frequent battery usage translates into 1,930-2,693 equivalent full cycles per year.

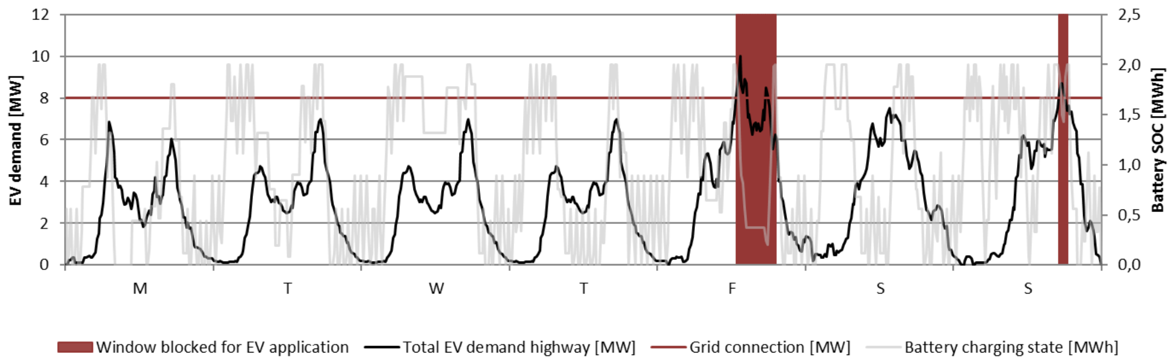

Fig. 6. Charging load curve along highways (black line). Horizontal red line indicates level of grid connection (here: 8 MW). During the red squares, the battery is not available for load shifting. Grey line: battery SOC (intraday trading). Own illustration.

5.3. Cost-efficiency of a stationary storage system

The annual TCO for the three battery types – Lead-Acid, Li-Ion and Redox-Flow – is shown in the following three figures. A positive TCO value indicates that the stationary storage does not economize. For the interpretation of the results, please note that the three figures have different axes.

For a city charging station with a 100 kW battery (case 1a), a Lead-Acid and a Redox-Flow battery can be cost-efficient, if intraday trading is performed (cf. Fig. 7). In contrast, a high power Li-Ion battery is unprofitable, even with intraday trading revenues. In this use case, approx. 1,000 additional full cycles are needed to exploit the potential of intraday trading. The arbitrage revenues – 2,532 €/a for the Lead-Acid and Redox-Flow battery and 3,287 €/a for the more efficient Li-Ion – are high enough to compensate for the shorter lifetime of the batteries. However, the profitability of intraday trading depends on the electricity price spreads that might be exploited. Here, we use historic market prices from 2017. For lower price spreads, profitability of the stationary storages might collapse. In addition, the return on investment is with less than 3% very limited. Accordingly, a high power stationary storage is only profitable for a city fast charging station (case 1a) under favorable conditions.

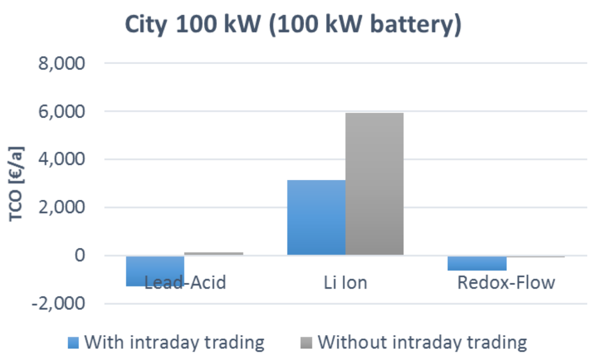

Fig. 7. TCO of a 100 kW stationary storage (city use case 1a). Own illustration.

In contrast, a city fast charging station with more powerful grid connection and thus with a smaller battery (case 1b) seems to be an interesting business case for stationary storages, because, under the assumptions made, all three battery types can economize. However, for this use case, intraday trading is not cost-efficient, mainly due to two reasons. First, the number of full-cycles increases due to the relatively smaller battery capacity: approx. 2,000 full cycles are needed. Second, also the shiftable load and thus arbitrage revenues decrease: revenues are 1,830 €/a for the

Li-Ion battery and 1,385 €/a for the other two battery types. Since profitability of the stationary storage systems is high for all technologies – the return on investment amounts to 8-10% for the Li-Ion and Redox Flow and to 35% for the Lead Acid battery –, we can conclude, that especially this use case is promising for the use of stationary storages.

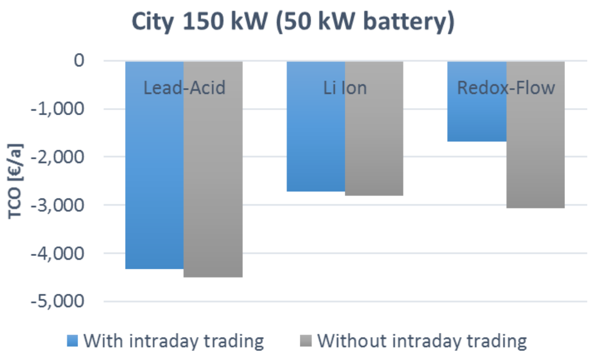

Fig. 8. TCO of a 50 kW stationary storage (city use case 1b). Own illustration.

Finally, for a highway charging station (case 2), conclusions are similar to use case 1a. The Lead-Acid battery is the only technology being profitable under the assumptions made and the return on investment is also limited (<5%). However, while for the Li-Ion battery yearly earnings from intraday trading of 73,574 € are high enough to compensate for the lower battery life due to ~2,000 full-cycles per year, revenues for the other two battery types are too low (55,827 €/a). Nevertheless, the use of a stationary storage at large highway fast charging stations is not always profitable and thus might need additional incentives or serve other purposes such as solar PV integration (onsite) or grid stabilization.

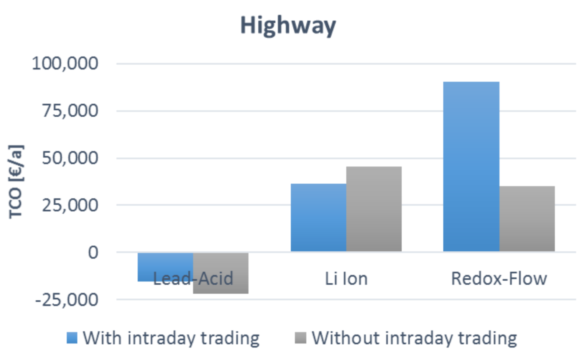

Fig. 9. TCO of a 2,000 kW stationary storage (highway; use case 2). Own illustration.

5.4. Break-even analysis

To analyze the impact of our assumptions on the results and to provide a decision-making support, we show the results of a break-even analysis, as summarized in the following three tables. We show the results for the case without intraday trading. The following tables show the value of the different cost parameters that would be necessary for the stationary storage to start to economize if all other parameters are kept constant.

As shown in Section 5.3, a Lead-Acid and a Redox-Flow battery can economize for a city charging station (100 kW battery) under current circumstances. However, also the Li-Ion battery could be operated profitably under slightly different circumstances such as higher grid connection cost or lower battery cost.

Table 5. Break-even analysis for different cost components for a city charging station with a 100 kW battery (use case 1a). Table entries show values that would be needed for a profitable operation of the stationary storage.

	Lead-Acid	Li-Ion	Redox-Flow
Total grid connection cost [€/100kW]	60,000	115,000	70,000
Specific battery cost [€/kWh]	120	375	330(1)
Calendar life [a]	8	57	11.5
Cycle life [# full cycles]	3,350	55,000	11,500

(1) if no power dependent price of the battery is assumed

Table 6 underlines the finding of Section 4.1: a stationary storage with 50 kW can be highly profitable at city fast charging stations.

Table 6. Break-even analysis for different cost components for a city charging station with a 50 kW battery (use case 1b).

	Lead-Acid	Li-Ion	Redox-Flow
Total grid connection cost [€/50kW]	22,000	42,000	55,000
Specific battery cost [€/kWh]	240	765	275(1)
Calendar life [a]	2	6	6
Cycle life [# full cycles]	1,500	11,000	10,000

(1) if no power dependent price of the battery is assumed

For a large scale stationary storage at highway stations either low battery cost or high grid connection cost are necessary. Lead-Acid batteries can be profitable under today's conditions, Li-Ion batteries are profitable for high but possible grid connection cost (cf. Gras, 2016).

Table 7. Break-even analysis for different cost components for a highway charging station with a 2,000 kW battery.

	Lead-Acid	Li-Ion	Redox-Flow
Total grid connection cost [€/2,000kW]	860,000	1,500,000	2,200,000
Specific battery cost [€/kWh]	120	410	370(1)
Calendar life [a]	4.5	15.5	15
Cycle life [# full cycles]	3,300	30,000	28,000

(1) if no power dependent price of the battery is assumed

5.5. Sensitivity analysis

In this section, we analyze the sensitivity of the results for parameters concerning the stationary storage, as addressed in the break-even analysis above. Although the assumed lifetime of the grid connection has an effect on the total cost of the stationary storage, the quality of the results, i.e. the general profitability of the stationary storage, does not change for an assumed lifetime in a range from 20 to 50 years. An analogous conclusion is valid for an interest rate between 2 and 7%. In our analysis, we assumed the operating expenditures of the stationary storage to comprise 2% of the investment. If these were higher, namely 5% of the investment, no battery type would be profitable at a city fast charging station with a 100 kW stationary storage (100 kW grid connection). For a city charging station with a smaller battery (50 kW), operating expenditures would have to comprise more than 12% of investments to make Li-Ion and Redox-Flow batteries unprofitable – a lead acid battery would still be profitable for operating expenditures in the order of 35% of the investment. For a highway charging station, the Lead-Acid battery would become unprofitable for operating expenditures comprising 7% or more of the investments.

Finally, a test for the sensitivity of the results for lower depth of discharge and capacity at end of life, respectively (cf. Table 2), shows that despite changing the total sum of yearly cost, it does not change the quality of our results with respect to the question whether the stationary storage might be cost-efficient or not.

In our main analysis, we examined a Li-Ion battery type with high durability, lifetime and cost (LTO cell chemistry). The following table summarizes the results for a Li-Ion battery type with lower cost, but also lower cycle life (NMC/LMO) and in addition a second-life battery. We find, analogous to Lead-Acid batteries, that the cost of 175 €/kWh for the NMC/LMO Li-Ion battery and 100 €/kWh for the second life battery are sufficiently low to allow for a cost-efficient operation of the stationary storage, despite the lower (cycle) life of these two battery types. As reference, the Li-Ion LTO battery analyzed in the main part of the paper (cf. Section 5.3) is also shown.

Table 8. Annual TCO of a battery storage for other battery types.

	City 100 kW (use case 1a)	City 50 kW (use case 1b)	Highway 2,000 kW (use case 2)
NMC/LMO Li-Ion	-1,400 €/a	-4,800 €/a	-34,000 €/a
Li-Ion second life	-1,500 €/a	-4,900 €/a	-38,000 €/a
Reference: Li-Ion LTO (see Section 5.3)	+5,950 €/a	-2,800 €/a	+45,600 €/a

Assumptions as in the main part, no intraday trading assumed.

The table shows TCO for no intraday trading to highlight the effect of different battery parameters on operation. The potential of intraday trading for the NMC and second life Li-Ion are qualitatively comparable to the potential of the Lead-Acid battery due to comparable parameters (cf. Table 3 for parameters).

6. Conclusions

We analyze the cost-efficiency of stationary storage systems and find different requirements for fast charging stations in cities and along highways. While charging stations in cities might come with lower charging power since drivers can use the charging time for other activities, such as running smaller errands, high charging power at fast charging stations along the highway is inevitable to keep charging times short, which leads to high load peaks in the order of 10 MW. Accordingly, while in the city grid connection cost might play a subordinate role, grid connection costs are high in the highway case.

Our findings indicate that especially batteries with low specific cost, such as the Lead Acid or second life Li-Ion batteries, are suitable for stationary storage application, since they allow for an economic operation for all of the analyzed use cases. Whereas the higher cycle life of a Li-Ion battery cannot compensate for its higher specific cost. According to our results, the most promising use case for a stationary storage is to shift demand. Accordingly, the most promising application is to only buffer the peak demand period, which comprises only several hours per week and to use the storage for demand shifting outside this time window. Since the charging load curve shows pronounced peaks on almost every day, demand shifting can be highly profitable. Accordingly, for a city charging station, a stationary storage might increase yearly incomes by up to 4,500 € (cf. Fig. 9). However, intraday trading is only profitable in one of the analyzed use cases (1a: larger battery at city fast charging station) and does not seem to be an interesting application for other use cases because battery prices are too high and electricity market price spreads are too low to compensate for the lower battery lifetime.

Mobility behavior is similar in different regions and within Europe. Although our results rely on specific charging load curves (at specific charger locations), we expect our general results therefore to be transferrable to other cities and highways. While the exact revenue figures depend on the specific course of the charge curve, the general finding that stationary storages can be operated profitably, rely only on the existence of pronounced peaks, both daily and weekly. Since these result from rush hour periods such as after-hours traffic, a similar course of the loading curve is likely in other cities and countries.

The economic efficiency depends strongly on the avoided network connection costs, the additional revenues, as well as the costs of the battery. Higher revenues are possible if the price spread on the intraday market increases or if the battery is used on other markets (e.g. frequency response reserve). Future analyses could take into account interactions between high battery usage and market revenues, e.g. by modelling battery degradation. In addition, the dimensioning of the battery could be determined by extending the operation optimization model in order to ensure the most economical battery size.

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References

Ahmadi, L., Young, S. B., Fowler, M., Fraser, R. A., and Achachlouei, M. A., 2017, A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems, Int J Life Cycle Assess, vol. 22, no. 1, pp. 111 124.

I. Safak Bayram, George Michailidis, Michael Devetsikiotis, Babak Parkhideh, 2012, Strategies for Competing Energy Storage Technologies for in DC Fast Charging Stations. IEEE SmartGridComm 2012 Symposium.

Bundesnetzagentur (BNetzA), 2019, Ladesäulenregister (charging station register). Federal Network Agency, Bonn, Germany.

K. Chaudhari and A. Ukil, 2016, TOU pricing based energy management of public EV charging stations using energy storage system, 2016 IEEE International Conference on Industrial Technology (ICIT), Taipei, 2016, pp. 460-465. doi: 10.1109/ICIT.2016.7474795.

Álvaro Cunha, F.P. Brito, Jorge Martins, Nuno Rodrigues, Vitor Monteiro, João L. Afonso, Paula Ferreira, 2016, Assessment of the use of vanadium redox flow batteries for energy storage and fast charging of electric vehicles in gas stations, Energy, https://doi.org/10.1016/j.energy.2016.02.118..

Jiaxi Deng, Jing Shi, Yang Liu, Yuejin Tang, 2015, Application of a hybrid energy storage system in the fast charging station of electric vehicles, IET Generation, Transmission & Distribution , doi: 10.1049/iet-gtd.2015.0110.

Egbue, O. and Long, S., 2012, Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions, Energy Policy, vol. 48, pp. 717 729.

EPEX SPOT, 2017, Prices from 2017 intraday auction.

Fraunholz, D., 2014, Identifikation von Kostenfunktionen für Kapazitätserweiterungsmaßnahmen im Stromverteilnetz: Identification of cost functions for capacity expansion measures in the power distribution network," Bachelor Thesis, Heilbronn University of Applied Sciences, Heilbronn, Germany.

Funke, S. Á., and Plötz, P., 2017, A techno-economic analysis of fast charging needs in Germany for different ranges of battery electric vehicles, Proceedings to the European Electric Vehicle Congress (EEVC), 14th 16th March 2017.

Funke, S. Á., Gnann, T., and Plötz, P., 2015, Addressing the Different Needs for Charging Infrastructure: An Analysis of Some Criteria for Charging Infrastructure Set-up, In: Green energy and technology, E-Mobility in Europe, W. Leal Filho and R. Kotter, Eds., Cham: Springer International Publishing, 2015, pp. 73 90.

Pablo García-Triviño, Juan P. Torreglosa, Luis M. Fernández-Ramírez, Francisco Jurado,2016, Control and operation of power sources in a medium-voltage direct-current microgrid for an electric vehicle fast charging station with a photovoltaic and a battery energy storage system, Energy, https://doi.org/10.1016/j.energy.2016.08.099.

GIZ, 2015, Markets for Battery Storage. Sub-sector analysis on the market potential for battery storage in Tanzania, German Society for International Cooperation (GIZ).

Marjan Gjelaj, Chresten Træholt, Seyedmostafa Hashemi, Peter Bach Andersen, 2017a, DC Fast-Charging Stations for EVs Controlled by a Local Battery Storage in Low Voltage Grids.

Marjan Gjelaj, Chresten Træholt, Seyedmostafa Hashemi, Peter Bach Andersen, 2017b, Cost-Benefit Analysis of a Novel DC Fast-Charging Station with a Local Battery Storage for EVs

Gohla-Neudecker, B., Maiyappan, V.S., Juraschek, S., & Mohr, S.L., 2017. Battery 2nd life: Presenting a benchmark stationary storage system as enabler for the global energy transition. 2017 6th International Conference on Clean Electrical Power (ICCEP), 103-109.

Gnann, T., 2015, Market diffusion of plug-in electric vehicles and their charging infrastructure. Stuttgart: Fraunhofer-Verl.

Gnann et al., 2017a, Öffentliche Ladeinfrastruktur für Elektrofahrzeuge. Ergebnisse der Profilregion Mobilitätssysteme Karlsruhe. Public charging infrastructure for electric vehicles. Results of the project Profilregion Mobilitätssysteme Karlsruhe.

Gnann, T., Jochem, P., Reuter-Oppermann, M., 2017b, Combining the demand for interim and opportunity charging - a case study from Stuttgart, Proceedings of the 30th International Electric Vehicle Symposium & Exhibition, EVS30, 9th - 11th October 2017.

Gnann, T., et al., 2018, Fast charging infrastructure for electric vehicles: Today's situation and future needs, Transportation Research Part D: Transport and Environment, vol. 62, pp. 314 329.

Gras, M., 2016, Netzanschlusskosten für Schnellladesäulen entlang süddeutscher Autobahnen: Grid connection costs for fast charging stations along southern German motorways, Bachelor Thesis, Karlsruhe Intitute of Technology, Karlsruhe, Germany.

Hautzinger, H., Kagerbauer, M., Mallig, N., Pfeiffer, M. and Zumkeller, D., 2013, Mikromodellierung für die Region Stuttgart-Schlussbericht-INOVAPLAN GmbH, Institute for Transport Studies at the Karlsruhe Institute of Technology (KIT).

Heymans, C., Walker, S. B., Young, S. B., and Fowler, M. 2014, Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling, Energy Policy, vol. 71, pp. 22 30.

Holger C. Hesse , Michael Schimpe , Daniel Kucevic and Andreas Jossen, 2017, Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids. Energies 2017, 10, 2107; doi:10.3390/en10122107.

IONITY GmbH, 2017. Pan-European High-Power Charging Network Enables E-Mobility for Long Distance Travel. Munich, Germany.

Jochem, P. , Brendel, C., Reuter-Oppermann, M., Fichtner, W., and Nickel, S., 2016a, Optimizing the allocation of fast charging infrastructure along the German autobahn, J Bus Econ, vol. 86, no. 5, pp. 513 535.

Jochem, P., Landes, P., Reuter-Oppermann, M., and Fichtner, W., 2016b, Workload Patterns of Fast Charging Stations Along the German Autobahn, Proceedings of EVS29-Conference, Montréal, Canada.

Kairies, K.-P., 2017, Battery storage technology improvements and cost reductions to 2030: A Deep Dive, Düsseldorf, Germany, Mar. 17 2017.

Daniel Kucevic, Cong Nam Truong, Andreas Jossen, Holger C. Hesse, 2018, Lithium-Ion Battery Storage Design for Buffering Fast Charging Stations for Battery Electric Vehicles and Electric Buses. NEIS Conference 2018 , Conference on Sustainable Energy Supply and Energy Storage Systems

Marano, V., Onori, S., Guezennec, Y., Rizzoni, G., and Madella, N., 2009, Lithium-ion batteries life estimation for plug-in hybrid electric vehicles, in IEEE Vehicle Power and Propulsion Conference, 2009: VPPC '09 ; 7 - 10 Sept. 2009, Dearborn, Michigan, USA.

Neaimeh, M., et al., 2017, Analysing the usage and evidencing the importance of fast chargers for the adoption of battery electric vehicles, Energy Policy, vol. 108, pp. 474 486.

Soodeh Negarestani, Mahmud Fotuhi-Firuzabad, Mohammad Rastegar, and Abbas Rajabi-Ghahnavieh, 2016, Optimal Sizing of Storage System in a Fast Charging Station for Plug-in Hybrid Electric Vehicles, IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, VOL. 2, NO. 4, DECEMBER 2016.

Plötz, P., Schneider, U., Globisch, J., and Dütschke, E., 2014, Who will buy electric vehicles?: Identifying early adopters in Germany, Transportation Research Part A: Policy and Practice, vol. 67, pp. 96 109.

Ralon, P., Taylor, M., Ilas, A., Diaz-Bone, H., and Kairies, K.-P., 2017, Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi.

Reinicke, F., 2015, Energieversorgung und -verteilung heute Einsatz von Großspeichern: Energy supply and distribution today - use of large storage facilities, Nov. 26 2015.

Lucas Richard & Marc Petit, 2018, Fast Charging Station with Battery Storage System for EV: Optimal Integration into the Grid. 2018 IEEE Power & Energy Society General Meeting (PESGM). DOI: 10.1109/PESGM.2018.8585856.

Reuter-Oppermann, M., Funke, S. Á., Jochem, P. , and Graf, F., 2017, How many fast charging stations do we need along the German highway network?, Proceedings of the 30th International Electric Vehicle Symposium & Exhibition, EVS30, 9th - 11th October 2017.

Vjekoslav Salapić, Mirna Gržanić, Tomislav Capuder, 2018, Optimal Sizing of Battery Storage Units Integrated Into Fast Charging EV Stations.

D. Sbordone, I. Bertini, B. Di Pietra, M.C. Falvo, A. Genovese, L. Martirano, 2015, EV fast charging stations and energy storage technologies: A real implementation in the smart micro grid paradigm, Electric Power Systems Research, https://doi.org/10.1016/j.epsr.2014.07.033.

Javier Serradilla, Josey Wardle, Phil Blythe, Jane Gibbon, 2017, An evidence-based approach for investment in rapid-charging infrastructure, Energy Policy, Volume 106, https://doi.org/10.1016/j.enpol.2017.04.007.

Schmidt, O., Hawkes, A., Gambhir, A., and Staffell, I., 2017, The future cost of electrical energy storage based on experience rates, Nat. Energy, vol. 2, no. 8, p. 17110.

StromNEV, 2005, Electricity Network Fee Regulation Ordinance.

Weiss, C., Chlond, B., Heilig, M., and Vortisch, P., 2014, Capturing the Usage of the German Car Fleet for a One Year Period to Evaluate the Suitability of Battery Electric Vehicles. A Model based Approach, Transportation Research Procedia, vol. 1, no. 1, pp. 133 141.

Wietschel, M., Gnann, T., Plötz, P., Funke, S. Á, 2015, Wie sieht ein bedarfsgerechter Ladeinfrastrukturaufbau für Elektrofahrzeuge in Deutschland aus? Energiewirtschaftliche Tagesfragen 65. Jg. (2015) Heft 12.

Wietschel, M.; Gnann, T.; Kühn, A.; Plötz, P.; Moll, C.; Speth, D.; Stütz, S.; Schellert, M.; Rüdiger, D.; Balz, W.; Frik, W.; Waßmuth, V.; Paufler-Mann, D.; Rödl, A.; Schade, W.; Mader, S., 2017, Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw. Studie im Rahmen der wissenschaftlichen Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie der Bundesregierung. Fraunhofer ISI, Karlsruhe, Fraunhofer IML, Dortmund, PTV Transport Consult GmbH, Stuttgart, Karlsruhe, TU Hamburg-Harburg, Hamburg, M-Five, Karlsruhe, Germany.

Libing Yang, Hajo Ribberink, 2019, Investigation of the potential to improve DC fast charging station economics by integrating photovoltaic power generation and/or local battery energy storage system, Energy, https://doi.org/10.1016/j.energy.2018.10.147.