FlyGrid – Integration of Energy Storage Systems into EV Fast Charging Infrastructure

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Abstract:

An increasing number of electric vehicles will challenge the present-day power system, especially on the low- and medium-voltage level. Energy storage systems might have the potential to mitigate grid loads substantially. Hence, in the project "FlyGrid," energy storage systems are integrated into electric vehicle charging infrastructure. Furthermore, the required design of these systems is determined in detail, considering numerous electric vehicle use cases. This work presents the project's previous results and conclusions acquired so far: The required specifications of energy storage systems strongly depend on the electric vehicle application, including its charging power and the number of installed charging points. However, even storage units with low capacity and moderate discharging power enable significant grid relief for the local power grid in most cases.

Keywords: Electric vehicle, distribution system, peak load shaving, energy storage system

1 Introduction

On both the European [1] and the national level [2], climate-neutrality shall be realized, inter alia, by transitioning towards clean electric mobility. However, future electric vehicle (EV) numbers will also challenge existing distribution systems [3]. On this account, new innovative solutions must be found to avoid costly grid expansions yet fulfilling the EV user's mobility needs. The integration of energy storage systems (ESSs) into EV charging infrastructure represents one of them. Nevertheless, integrating decentralized ESSs into future grid planning processes certainly requires detailed knowledge about their required specifications depending on the supplied EV use case. The research project "FlyGrid" [4] tackles this problem by identifying ESS specifications required for covering short-term charging peak loads of various e-mobility use cases.

1.1 Project FlyGrid and structure of this work

The project "FlyGrid" [4] is funded by the Austrian "Klima- und Energiefonds" via the Austrian Research Promotion Agency (FFG) program "Leuchttürme eMobilität". Within the project, high-performance ESSs are integrated into (fast-) charging stations as follows (Fig. 1): Distribution system, ESS, and charging infrastructure are connected to a DC voltage link via AC/DC,

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DC/AC or DC/DC inverters, comparable with Dragicevic et al. (2014) [5] and Yan et al. [6]. Future EV charging demands are either supplied by the distribution system, the ESS (in case of available energy capacity), or both.

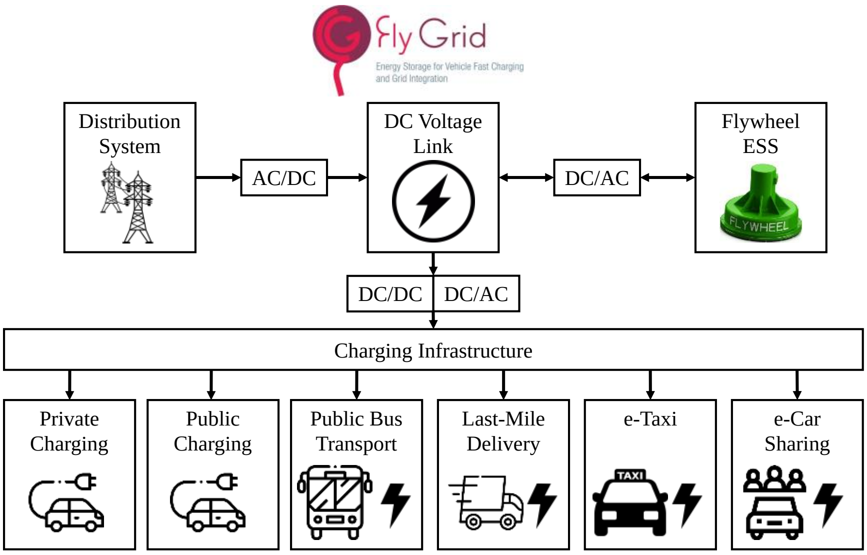

Figure 1: Scheme of the project "FlyGrid": Grid integration of future e-mobility use cases by implementing a flywheel energy storage system (ESS) [4]

Notwithstanding the above, both AC and DC power can be provided by the charging point. Hence, even at the low-voltage level, high charge-power can be reached while at the same time stabilizing the grid. Regarding the short-term supply of high-power EV charging, flywheel ESS provide substantial benefits compared to battery ESS [7–10]: High life cycle number, high power density, fast access time, low maintenance effort, small environmental impact, and the independency of power and energy content. In addition, flywheel ESSs allow lower investment and operation costs compared to supercapacitors [5,11]. As a result, flywheel ESSs are selected as energy storage technology in the project "FlyGrid". However, the project's results and conclusions are also applicable to other storage technologies. Before testing the application of a flywheel ESS based on real-life demonstrations, the project "FlyGrid" identifies its specifications required for supplying future e-mobility in detail. Therefore, e-mobility use cases (Table 1) with significant environmental and economic importance are selected for investigation.

Table 1: E-mobility use cases and their respective charging power considered in the project "FlyGrid"

EV Use Case		Charging power (kVA)
1	Charging at public parking lots	3.7 – 44.0
2	EV car sharing	3.7 – 100.0
3	Highway fast charging	50.0 – 350.0
4	Public charging at shopping centers	3.7 – 100.0
5	Electrified busses	100.0 – 600.0
6	Electrified taxies	3.7 – 100.0
7	Electrified last-mile delivery trucks	100.0 – 350.0

Parts of the project's previous results have already been published in Thormann et al. (2019) [12], considering use case 1, and in Thormann et al. (2021) [13], considering use cases 3, 5, and 7. This work describes the methodology (Section 2) applied in the project "FlyGrid", and summarizes all use cases' results (Section 3). Finally, Section 4 provides the most significant conclusions from the project acquired so far and an outlook regarding further research questions.

2 Methodology

In the project "FlyGrid", realistic charging patterns and loads are modeled based on real-life mobility data (Section 2.1). These charging loads of EVs are integrated into existing distribution networks to identify potential grid impacts of EV charging. Based on identified grid restrictions, ESS specifications required for counteracting them are determined in detail (Section 2.2).

2.1 Modeling of realistic charging loads

In the first step of the project, realistic annual time-series (1 min. temporal resolution) of EV charging loads are modeled stochastically for each of the pre-defined EV use cases (Table 1). Therefore, the following aspects are taken into account:

- The spatial distribution of charging points
- Individual mobility patterns (time of charging and covered distance)
- EV model specifics (battery capacity, specific energy consumption, and charging efficiency)
- Charging power (Table 1)

The spatial distribution of charging grids is derived from real-life locations of public parking lots (Use case 1), car-sharing terminals (2), highway service stations (3), shopping centers (4), bus stations (5), taxi terminals (6) and hubs of last-mile delivery vehicles (7). The time of charging and the distance covered before charging are both determined stochastically using statistical data [14–17] (in the form of cumulative distribution functions) and random numbers (Fig. 2).

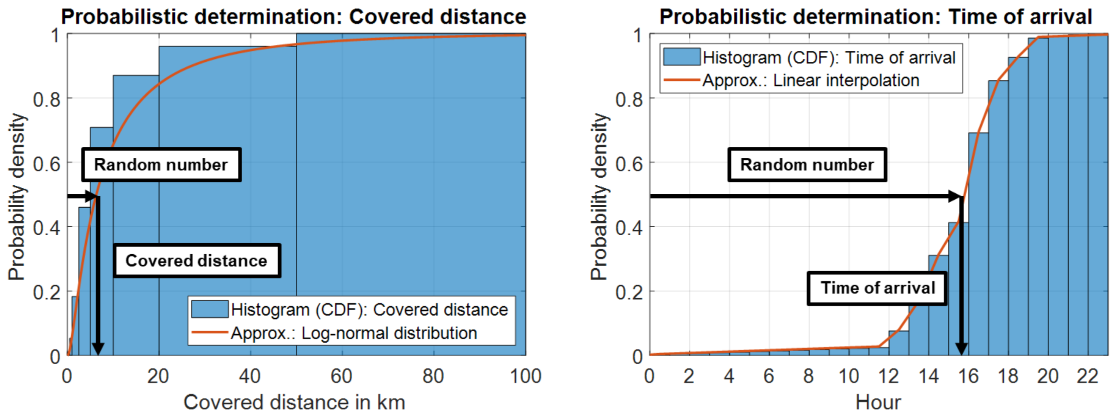

Figure 2: Probabilistic determination of the covered distance (left) and the time of arrival (right) using the cumulative distribution function (CDF) and random numbers

Besides temporal mobility patterns, the timely-resolved modeling of EV loads requires the consideration of the state-of-the-art EV model specifics. Battery capacities, specific energy consumptions, and charging efficiencies applied in this project are described in Thormann et al. (2020 and 2021) [13,18]. For analyzing potential grid impacts caused by EV charging, numerous scenarios regarding various charging powers are analyzed for each use case. Based on these four aspects, EV charging profiles are modeled for each use case, either by using measured charging data [18] or rectangular charging curves with constant charging power during the charging process.

2.2 Determining required ESS specifications

The modeled EV charging loads are then virtually integrated into grid models of existing real-life distribution power grids, operated by Energienetze Steiermark GmbH. Long-term (one year) load flow simulations are performed to identify thermal grid restrictions of lines or transformers triggered by future EV use cases. In the next step, the capacity and power of decentralized ESSs required to counteract these thermal grid restrictions are determined in detail. Therefore, the apparent power available in the power grid ($S_{Available}$) is calculated in each time step *t* using the nominal power of grid elements ($S_{max,therm}$) and the grid elements' initial load without EVs ($S_{initial}$) according to Eq. 1.

$$S_{Available}\ (t) = S_{max,therm} - S_{initial}\ (t) \tag{1}$$

$$S_{ESS}(t) = S_{available}\ (t) - S_{EV}(t) \tag{2}$$

$$Energy_{ESS}(t) = Energy_{ESS}(t-1) + \int_{t-1}^{t} P_{FESS} * dt \tag{3}$$

$$required\ ESS\ discharging\ power = \frac{\min(S_{ESS}(t))}{\eta_{Discharging}} \tag{4}$$

$$required\ ESS\ capacity = \min(Energy_{ESS}(t)) \tag{5}$$

Each ESS's apparent power (S_{ESS}) is determined by subtracting the EV charging load from the available capacity at the particular power grid location (Eq. 2). Thus, ESSs are discharged ($S_{ESS} < 0$) when EV charging loads exceed the available capacity of the grid. After discharging triggered by peak shaving needs, the supplied amount of energy is recharged ($S_{ESS} > 0$) into the ESS during off-peak periods, when the available grid capacity exceeds EV charging demands. Furthermore, the amount of energy stored in the ESS ($Energy_{FESS}$) is calculated in each time step *t* using Eq. (3): The amount of energy stored in the ESS decreases during ESS-discharging and increases during ESS-charging. Furthermore, we limit the energy stored in the ESS with [-∞; 0] to ensure that ESSs only recharge the amount of energy they have provided during previous peak shaving services. Since flywheels are selected as storage technology in this study, the following characteristics are applies specifically for this storage technology: A charging and discharging efficiency of 90 % [19] is applied to model realistic operation of the flywheel ESS. Furthermore, a linear approximation between dissipation losses and the state of charge of the flywheel ESS is implemented [20]. Hence, dissipation losses vary between 0.5 kW (100 %) and 0.0 kW (0 %), depending on the flywheel's state of charge. Finally, the required ESS discharging power and capacity are identified for each use case and each charging power (Table 1) using Eq. (4) and (5).

3 Results

This section provides the ESS discharging power and capacity per charging point required to cover short-term EV charging loads and prevent local grid restrictions. Regardless of the supplied use case, both – power rating and energy content - strongly depend on the actual EV charging power: The higher the EV charging power, the higher the capacity and discharging power requested by the ESS per charging point. Of course, the actual ESS specifications depend on the particular distribution grid and its local load conditions. Furthermore, the required ESS specifications correlate with the number of supplied charging points. The more charging points are supplied by the ESS, the more energy must be stored per charging point to counteract local grid overloads. Similarly, the required ESS discharging power per charging point increases the more charging points are installed.

Based on these correlations, the applied design method identifies a broad spectrum of required ESS specifications for each use case, illustrated in Fig. 3 (ESS capacity) and Fig. 4 (ESS power). Considering low-power charging use cases (1, 2, 4, and 6), the required ESS capacity (Fig. 3) varies between 0.5 and 158 kWh per charging point, with medians between 0.5 (Use case 2) and 1.5 kWh (Use Case 4). Furthermore, integrated ESSs must provide a discharging power between 0.25 and 53 kVA per charging point to supply these use cases (Fig. 4).

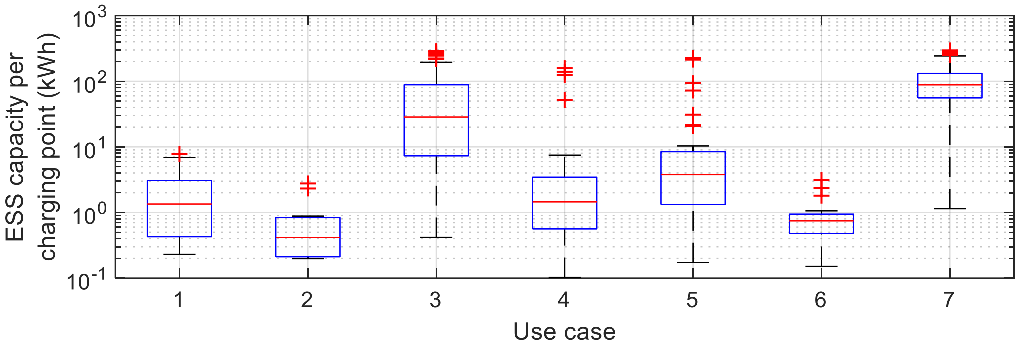

Figure 3: Spectrum of ESS capacity per charging point supplying various EV use cases

For example, a ESS integrated into an electric taxi charging station with six charging points and charging power of 22 kVA each requires at least a capacity of 2.2 kWh and a discharging power of 24.6 kVA. The supply of high-power charging EV uses cases (3, 5, and 7), one the other hand, requires a ESS capacity (Fig. 3) between 0.17 and 295 kWh, with a median between 4 (Use case 5) and 88 kWh (Use case 7).

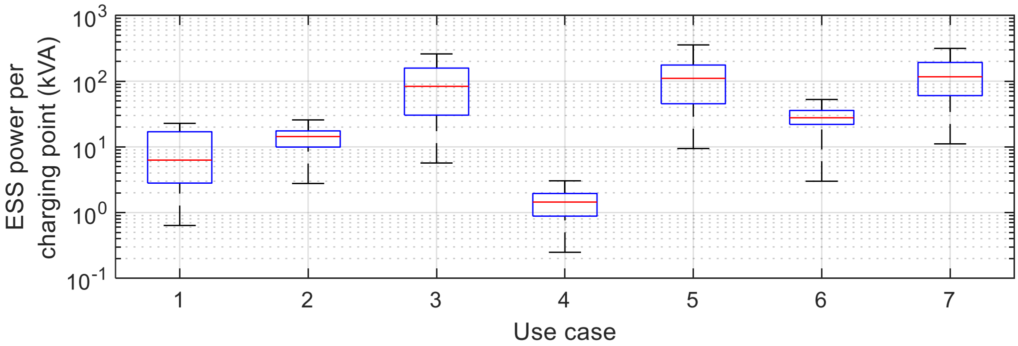

Figure 4: Spectrum of ESS power per charging point supplying various EV use cases

The short-term covering of peak loads requests ESS discharging power (Fig. 4) between 6 and 356 kWh per installed charging point, with medians of 83 (Use case 3), 110 (5), and 117 kVA (7). Despite the broad spectrum of ESS specifications, most charging demands of future EV use cases can be supplied by integrating a ESS with relatively low capacity (e.g., 5 kWh) and moderate power (e.g., 100 kVA) per charging point. This tendency correlates with the fact that most (95.1 %) individual trips are shorter than 50 km [14], corresponding to an energy demand of about 10 kWh. However, EV applications requiring higher ESS capacity and discharging power may be supplied either by larger ESSs, or a modular approach of several ESS units.

4 Conclusions and Outlook

The modeling of timely-resolved charging profiles based on accurate mobility data demonstrates crucial differences in the charging behavior of varying EV use cases. When applying these realistic charging profiles, even numerous charging points can be integrated into existing low- and medium-voltage grids considering EV charging with moderate charging power (up to 44 kVA). Furthermore, the project’s previous results confirm that any kind of energy storage can severely mitigate potential grid congestions in many cases. However, the required ESS specifications depend significantly on the individual EV use case, EV charging power, and the grid location. The demonstrated discrepancies between EV use cases inhibit the design of one single ESS unit suitable for all considered applications. Nevertheless, most EV cases can entirely be supplied by the ESS specifications of 100 kVA discharging power and 5 kWh capacity per ESS module. Considering flywheel ESSs, for example, e-mobility use cases with higher energy- and power demands may require a modular approach of several flywheel units. Thereby, even high-power charging EV applications, e.g., opportunity charging of electric busses, can be supplied in a grid-friendly way considering a moderate number of charging points and moderate charging power.

Of course, the application of ESSs must also be evaluated in terms of the total investment and operation costs. Therefore, future work should compare the integration of different ESS technologies with demand-side measures or classic grid reinforcements in terms of overall costs. Flywheel ESS, for example, can provide significant economic benefits when supplying high-power EV charging demands characterized by numerous, though short, charging processes (e.g., electric busses), demonstrated in Thormann et al. (2021) [13].

5 Acknowledgments

This work is part of the project “FlyGrid” (www.flygrid.tugraz.at), funded by the Austrian “Klima- und Energiefonds” via the Austrian Research Promotion Agency (FFG) program “Leuchttürme eMobilität” (grant number 865447).

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