EVALUATING THE POTENTIAL OF FUTURE E-MOBILITY USE CASES FOR PROVIDING GRID ANCILLARY SERVICES

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Abstract

The fostered implementation of volatile renewable energy sources will trigger a raising demand of grid ancillary services in the upcoming years. However, future electrified road vehicles provide significant energy storage capacities, since they are unused for most of the time. In this regard, this study analyses for various electric vehicle (EV) use cases the potential for providing grid ancillary services based on the vehicle-to-grid technology. Therefore, we estimate the future demand of ancillary services in 2030 in terms of redispatch measures and control reserve. Real-life EV mobility patterns demonstrate, that EVs are perfectly suitable for the provision of ancillary services, even with low discharging power. Assuming a sufficient EV-penetration, private EVs charging at home or at work may cover a substantial share of required grid ancillary services. Besides EV users' mobility patterns, long-term load flow simulations illustrate the limitation of possible grid ancillary services due to local grid restrictions, especially with high discharging and charging power. Consequently, an increase of charging and discharging power only slightly raises the actual share of provided grid ancillary services compared to a low-power bidirectional power exchange between grid and EV.

1. Introduction

The climate and energy transition, pursued at a national (e.g. [1]) and European level [2], strongly depends on an area-wide expansion of renewable energy sources (RES) [3, 4]. Besides ecological benefits, this transition faces the existing power system with major challenges: A forced generation by wind- or photovoltaic plants will increase the volatility of the future electricity system. Consequently, it raises the required level of control reserve capacity, in order to balance temporal and spatial deviations between generation and consumption and to stabilize grid frequency. In fact, recent studies [5, 6] indicate this trend especially in terms of secondary- (automatic frequency restoration reserve - AFRR) and tertiary (manual frequency restoration reserve - MFRR) control reserve. Additionally, the increase of (decentralized) generation by RES could exceed local power demands during off-peak periods, which requires a spatial balance with other grid- or control areas. However, in case of imminent congestions in the transmission system, the transmission system operator must intervene in the form of congestion management measures (redispatch) [7]. Recent years show a significant increase of these measures and resulting costs [7], which is going to be continued in the upcoming years [8]. In summary, the targeted energy and climate transition results in an increased demand for flexibility options within an integrated energy system. Another important pillar in future climate and energy transition strategies could provide this form of flexibility [1]: The electrification of the transport sector. In Austria, for example, the path towards carbon-neutrality include a carbon-free traffic sector until 2050 [3]. Consequently, monetary and non-monetary incentives as well as future price reducing effects will increase electric vehicle (EV) numbers. In addition to private cars, the decarbonization of the traffic sector crucially depends on the electrification of other e-mobility use cases, like last-mile delivery vehicles, taxies or car-sharing. However, besides beneficial effects towards decarbonization, the future energy system could benefit from increasing EV numbers: Since road vehicles are parked most of the time [9, 10], EVs represent significant energy storage capacities [11], connected to the power grid. Therefore, the vehicle-to-grid (V2G) technology allows bidirectional charging and discharging of EVs. Hence, EVs are able to feed power back into the power grid, and can thereby be used as (local) energy storage system. Consequently, future EVs allow the control of both the power demand from the grid and the power feed into to the grid. Both can be used for providing ancillary services [5, 10, 11]. Despite the currently low EV-penetration [12], the potential of future e-mobility for providing grid ancillary services must be identified at an early stage.

1.1. State of Research

Recent studies address this issue by considering varying forms of grid ancillary services. While Turton and Moura (2007) [13] declare peak load shaving as the most promising V2G-application of future EVs, most studies focus on the

provision of control reserve: Schuller and Rieger (2013) [14] demonstrate economic benefits when participating in the AFRR- and MFRR-market. Similarly, the German Fraunhofer Institute (2013) [11] conclude, that the provision of AFRR and MFRR allows substantial cost savings for EV users. Hermann et al. (2011) [15] define MFRR as the most promising field of application. Kempton and Tomic (2004) [9] recommend the usage of future EVs for providing MFRR and frequency containment reserve for the power grid. Finally, Schill et al. (2016) [5] also determine the highest potential of EVs for delivering control reserve, whereas cost benefits by arbitrage activities are negligible. Furthermore, they demonstrate that the V2G-concept provides significant cost savings, compared to an exclusive control of grid demand (grid-to-vehicle).

1.2. Main Contributions and Structure of this Work

In summary, recent studies focus primarily on the provision of control reserve, provided by passenger EVs parked at home or at work. To the authors' best knowledge, the impact of this intervention on local grids is not investigated. On this account, this study includes additional e-mobility use cases, like last-mile delivery EVs, electric taxies or electric car-sharing. In addition to control reserve, we also investigate the provision of future redispatch measures based on these EV use cases. Furthermore, the determined (theoretical) potential of provided grid ancillary services is examined in terms of potential grid restrictions, by performing long-term load flow simulations. Therefore, this work is structured as follows: Sections 2.1 and 2.2 describe the applied methodology for determining the future demand of grid ancillary services and for deriving realistic EV charging patterns. The evaluation of each use case's theoretical service potential (2.3) as well as the performed grid simulations (2.4) are described in further sections. Finally, this work's results are illustrated in section 3 and concluded in section 4.

2. Methodology

2.1. Identifying the future demand of grid ancillary services

In general, grid ancillary services can be provided for the power grid in a negative (decrease of power feed or rather increase of power demand) or positive (increase of power feed and decrease of power demand) form. However, in 2019 the demand of positive redispatch- (1 859 GWh), AFRR- (310 GWh) and MFRR-services (19 GWh) required a total energy amount of 2 188 GWh in Austria [7]. In contrast, their negative equivalents result in a seven times lower total energy demand, and are therefore neglected in this study. Moreover, other forms of grid ancillary services, e.g. frequency containment reserve, spinning reserve or virtual inertia, are also excluded. According to the Austrian transmission system operator (APG) [7], redispatch measures were required on 228 days in 2019, primarily between 10:00 and 19:00 (Fig. 1).

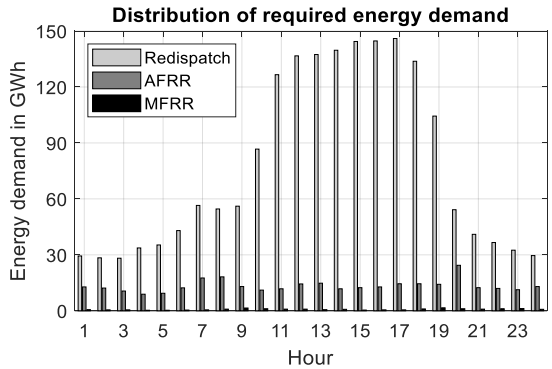

Fig. 1 Temporal distribution of annual energy demand in 2019 required by redispatch measures, automatic frequency restoration reserve (AFRR) and manual frequency restoration reserve (MFRR) [7]

AFRR (365 days) and MFRR (176 days), on the other hand, show rather constant demand throughout the day. Based on the data from 2019, we estimate the future demand of positive AFRR and MFRR in 2030 by assuming an increase by 23 % and 52 % respectively [6, 16]. Considering redispatch measures due to local grid congestions, we expect an increase of 18.8 % till 2030 in terms of required energy demand [8]. This results in respective energy demands of 2 209 GWh (redispatch), 381 GWh (AFRR) and 29 GWh (MFRR) in 2030. While scaling the annual energy demand of grid ancillary services (from 2019 to 2030), their temporal characteristic in 2030—hourly distribution throughout the day (Fig. 1) and days of request—are adopted from 2019.

2.2. Modelling of EV Charging Patterns

In order to evaluate the potential of future e-mobility for providing grid ancillary services, this study takes the following EV use cases into account:

- UC 1: Private charging of passenger EVs at home
- UC 2: Private charging of passenger EVs at work
- UC 3: Electrified station-based car-sharing fleets
- UC 4: Electrified taxi fleets
- UC 5: Electrified last-mile delivery fleets

For each use case, realistic mobility patterns are modelled based on real-life traffic data [17-21], including the following indicators: time of departure, time of arrival, covered distance per trip and number of trips per day. Applying these mobility patterns allows us to estimate the temporal distribution of parking vehicles for each use case (Fig. 2). Furthermore, we apply these mobility data in order to determine average covered distances for each use case depending on the day of the week (Table 1). In a next step, we use these mobility patterns to derive use case-specific charging patterns: To determine the maximum V2G-potential, each vehicle is immediately connected to the charging point after its arrival.

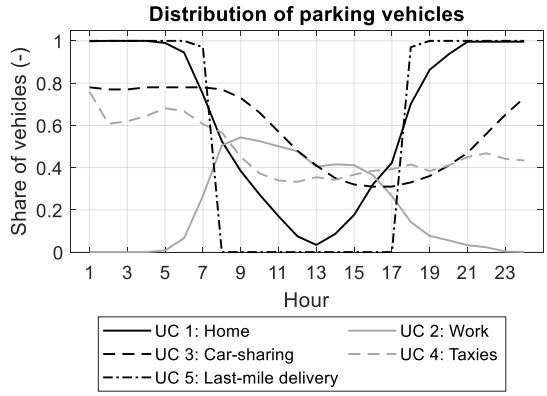

Fig. 2 Temporal distribution of parking vehicles considering varying EV use cases

The EVs' energy demands are determined by using an average energy consumption of 0.23 kWh/km [22] considering passenger EVs (UC 1 – 4) and 0.40 kWh/km [21] considering e-vans (UC 5), including the respective charging efficiency. Furthermore, each vehicle is equipped with an average battery capacity of 47 kWh (UC 1 – 4) [22] and 60 kWh (UC 5) [21].

Table 1 Average covered distance per trip (Workday – Saturday – Sunday) for each use case [17-21]

Use Case	Average covered distance (km)
UC 1: Charging at home	10.3 – 16.8 – 18.8
UC 2: Charging at work	13.1 – 15.2 – 18.7
UC 3: e-car-sharing	51.5 – 51.5 – 51.5
UC 4: e-taxies	11.9 – 12.9 – 12.5
UC 5: Last-mile delivery	85.0 – 85.0 – 85.0

Finally, EVs' charging patterns include state-of-the-art charging power, available at each charging point. Therefore, two scenarios, from low (3.7 kVA) to high EV power (11.0 kVA), are analysed for each use case respectively, with a power factor of 0.97 (leading) [22].

2.3. *Analysing the Potential for Providing Grid Ancillary Services*

The potential of varying EV use cases for providing grid ancillary services is estimated by confronting the determined future demand (2.1) with modelled charging patterns (2.2). Therefore, this study considers use case-specific fleets, located in the supply area of a selected suburban medium-voltage (MV) grid. Assuming one vehicle per household, the number of vehicles parking at home is derived for each MV/low-voltage-substation from the number of supplied households (Table 2). Furthermore, the number of vehicles driving to work is provided by traffic analysis [17] for each day of the week. Vehicle fleets of UC 3-5 are determined by identifying present-day car-sharing-, taxi- and last-mile delivery locations, using geographic information data [23].

Table 2 Number of considered vehicles depending on the EV use case and the day of the week [17, 23]

Use Case	Mo - Fr	Sa	Su
UC 1: Charging at home	12 402	12 402	12 402
UC 2: Charging at work	11 575	4 630	4 630
UC 3: e-car-sharing	85	85	85
UC 4: e-taxies	1 250	1 250	1 250
UC 5: Last-mile delivery	58	58	58

The number of EVs, on the other hand, depends on the particular penetration of e-mobility, which is varied between 20 – 100 % in this study. For each use case's EV-fleet, demand-oriented discharging behaviour is modelled for analysing their grid support potential. Therefore, all vehicles are aggregated to one virtual power plant and controlled by one central control unit within the following framework conditions:

- Same power and efficiency is assumed for charging and discharging of EVs (c.f. [24, 25])
- Recharging of EVs is interrupted or limited in case of grid ancillary service needs
- The planned time of departure as well as the targeted state of charge (SOC) is defined by each vehicle user and accessible for the control unit
- Parking EVs are available for the provision of grid services, until their targeted SOC can no longer be recharged within the remaining parking period
- EV batteries are maximally discharged to a SOC of 50 %, in order to meet EV users' (unplanned) mobility needs

Finally, these charging- and discharging patterns of EV-fleets are contrasted with the Austrian demand of grid ancillary services (2.1). Thereby, this study illustrates the share of nationwide grid services, deliverable by local EV-fleets supplied by one MV grid.

2.4. *Determining Potential Limitations due to Grid Restrictions*

Besides the limitation due to mobility patterns, the provision of grid ancillary services may be restricted due to local grid congestions. Therefore, this study performs long-term grid simulations (one year) with a time resolution of one hour, using the software NEPLAN. The MV-grid selected for this study represents a suburban region. It is connected to one distribution substation, transforming high-voltage (HV; 110 kV) into MV (20 kV) by two three-phase transformers with a nominal power of 40 MVA each. Both HV/MV-transformers are equipped with an on-load tap changer on the HV side, providing a controllable bandwidth of 2 % of the nominal voltage. Eleven feeders supply a total number of 406 MV/LV-substations via cable (35.8 % of the total length) or overhead lines, resulting in a total line length of 356 km. For performing long-term grid simulations, each of the 406 MV/LV-substations is depicted by annual time series: In

addition to electrical load and generation of conventional grid customers, these time series include charging- and discharging profiles of EVs connected to each particular substation. Potential grid limitations are determined based on inadmissible voltage (V) characteristics (96.5 % > V > 105.5 % of nominal voltage) and thermal overloads.

3. Results

Future e-mobility's potential for providing redispatch measures, AFRR and MFRR is illustrated based on the provided share of Austrian annual demand. Naturally, the provided energy increases with raising EV-penetration and, thereby, raising EV numbers: While all use cases combined can provide 0.5 % (low EV power, i.e. 3.7 kVA) of redispatch measures (in terms of energy) at an EV-penetration of 20 %, a complete electrification (100 %) of all use cases covers 2.3 % (Fig. 3) of the Austrian demand.

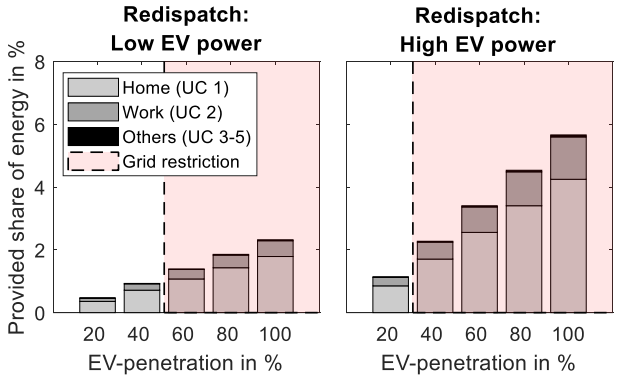

Fig. 3 Use case-specific share of redispatch measures in terms of provided energy, considering low (3.7 kVA) and high (11 kVA) EV power

In contrast to redispatch measures, which are primarily required between 10:00 and 19:00, AFRR and MFRR are requested rather constantly throughout the day (Fig. 1). Based on EV users' mobility patterns (Fig. 2), these forms of grid services enable a much higher potential considering their provision by future EVs: 6.4 % (AFRR) and 11.5 % (MFRR) of the Austrian demand at an EV-penetration of 20 %; 27.0 % (Fig. 4) and 46.7 % (Fig. 5) at an EV-penetration of 100 %. Regardless the form of grid ancillary service, charging and discharging with higher power theoretically increases EVs' potential significantly. Considering an EV-penetration of 60 %, the increase of EV power (to 11 kVA) allows a 2.4- (redispatch), 2.2- (AFRR) and 1.9-times (MFRR) higher share of grid ancillary service compared to low EV power (3.7 kVA). Thus, especially the provision of redispatch measures shows a strong correlation between available charging and discharging power and EVs' theoretical potential (Fig. 3). Based on the selected vehicle numbers (Table 2) and parking characteristics (Fig. 2), use case *private EVs parked at home* (UC 1) provide the most relevant share for all investigated grid services.

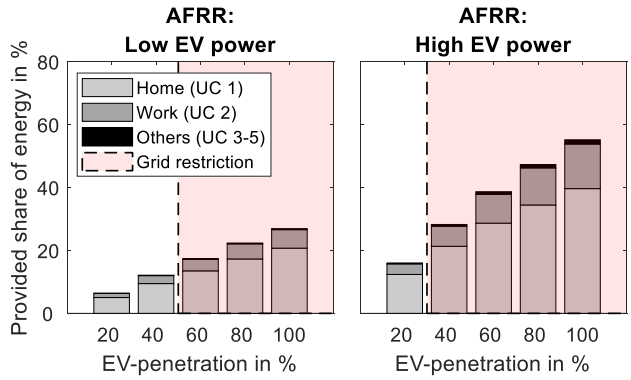

Fig. 4 Use case-specific share of automatic frequency restoration reserve (AFRR) in terms of provided energy, considering low and high EV power

Considering for instance a 60 % EV-penetration and low power, 1.1 % (redispatch), 13.5 % (AFRR) and 23.9 % (MFRR) might be provided respectively. The pooling of EVs parking at work and other use cases allows additional 0.32 % (Fig. 3), 3.9 % (Fig. 4) and 7.4 % (Fig. 5) of provided grid services.

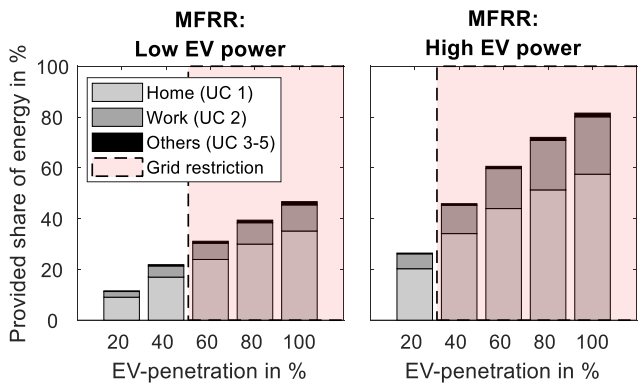

Fig. 5 Use case-specific share of manual frequency restoration reserve (MFRR) in terms of provided energy, considering low and high EV power

Nevertheless, the presented theoretical potential of bidirectional power exchange must be transmitted by local power grids. Considering the analysed suburban MV grid for example, long-term grid simulations reveal local grid congestions depending on the available discharging power: Low-power discharging of EVs (3.7 kVA) allows a maximal share of 0.9 % (redispatch), 12.1 % (AFRR) and 21.9 % (MFRR) at an EV-penetration of 40 % without any grid restrictions. The provision of grid ancillary services by larger EV-fleets (EV-penetration of 60 % and higher) triggers inadmissible voltage characteristics and thermal congestions (e.g. Fig. 3). Furthermore, bidirectional power exchange between grid and EV with 11 kVA is restricted to 20 % of vehicles. Consequently, an increase of EV power (from 3.7 to 11.0 kVA) only slightly raises the actual share of provided

grid ancillary services: 1.1 % (redispatch), 16.0 % (AFRR) and 26.4 % (MFRR).

4. Conclusions

This study demonstrates the suitability of various EV use cases for providing future grid utility services. Especially EVs parked at home or at work enable a substantial contribution to the future demand of grid ancillary services. Furthermore, even small fleets of e-taxies, e-carsharing or electric last-mile delivery vehicles might provide considerable grid support due to long parking periods. Although, the provision of redispatch measures by local EVs is rather low compared to a participation in the AFRR- and MFRR-market, due to temporal discrepancies between grid demand and parking periods. Considering the selected suburban MV-grid, the provision of grid ancillary services is strongly limited due to local grid restrictions, especially in case of high-power bidirectional power exchange between power grid and EVs. Besides limitations due to mobility patterns (social) or grid restrictions (technical), the provision of future grid ancillary services will strongly depend on legal and economic framework conditions for EV users. Consequently, future work should combine all of these aspects (technical, social, legal and economic) when evaluating EVs' potential for providing grid services.

5. Acknowledgements

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