Demonstrating Electric Vehicle Flexibility via Stationary BESS Aggregated into a Virtual Power Plant

Abstract:

The growing integration of electric vehicles (EVs) into power systems poses both challenges and opportunities for grid flexibility. Although Vehicle-to-Grid (V2G) technologies show strong potential, their real-world potential remains uncertain due to user, market, and technical constraints. A data-driven assessment of EV flexibility under realistic operating conditions is therefore needed.

This paper introduces a novel methodology for practical evaluation of EV flexibility by emulating V2G behaviour using a stationary Battery Energy Storage System (BESS) aggregated into a Virtual Power Plant (VPP). The approach combines statistical mobility data, historical grid load and market data to construct aggregated representative EV profiles for selected use cases (UCs) tailored to distinct flexibility services.

A multi-actor demonstrator was deployed in an operational distribution grid in Velenje, Slovenia, enabling nine VPP activations of the BESS with selected EV profiles. Three activations were examined in detail, focusing on a work charging and its provision of local flexibility services, manual frequency restoration reserve (mFRR), and automatic frequency restoration reserve (aFRR). Performance, quantification of V2G flexibility for multiple services and grid impact were evaluated through real measurements from the BESS, VPP, and secondary substation, alongside three indices—*Flexibility*, *V2G_utilization*, and *BESS_response*.

Results reveal that flexibility contributions differ across UCs and service types. Work charging showed the highest potential for local services, with fleet aggregation best suited for mFRR and home charging most effective for aFRR. V2G utilization reached 100% for the home and EV fleet UCs for provision of local services. Findings advance understanding of EV flexibility for stakeholders.

Key words: Vehicle-to-Grid (V2G); Battery Energy Storage System (BESS); Flexibility services; Balancing services; Aggregated representative EV profiles; Multi-actor demonstrator

1. Introduction

The increasing adoption of electric vehicles (EVs) is reshaping power systems by introducing new dynamic, variable and decentralized loads, which intensify the demand for flexibility provision. Flexibility is a key enabler for stable, efficient, and sustainable grid operation, allowing the integration of renewable energy sources (RES) while maintaining critical parameters such as voltage, frequency, and power balances at both local and national levels [1-2]. Beyond supporting system reliability, flexibility enhances the optimal use of energy resources and enables innovative market mechanisms that bridge technological development with implementation — making it a cornerstone of the green energy transition. To unlock this potential, local and national flexibility markets present a viable solution to support local flexibility procurement and activation. In Europe, the establishment of local flexibility markets (LFMs) has become a strategic priority, consistent with the EU's Net Zero goals and the increasing demand for flexibility across power systems [3].

In this context storage systems play a crucial role in Europe's transition to electrification, digitalization, and a sustainable economy, underpinning the broader goals of decarbonization and innovation [1]. Battery energy storage systems (BESSs) are a renowned flexibility source for the provision and activation of flexibility services required for stable operation of the power grid [4-5]. They also have a good utilization potential for participation in energy markets as stated in [6].

BESSs can be broadly classified into stationary and mobile storage solutions, each of which plays a distinct role within the evolving energy ecosystem. Stationary BESSs are typically installed at permanent locations and are already widely deployed as part of power grid flexibility measures. By contrast, mobile BESSs, most commonly represented by the batteries of EVs, offer dynamic deployment capabilities, uncertain connection and localized flexibility [7-8]. With the increasing electrification of mobility, mobile BESSs are gaining attention (rise in capacities and better performances), strategic importance, and flexibility potential for participation in flexibility services on energy markets [9].

Recent models [10] suggest that the global fleet of EVs could provide 32–62 TWh of flexible mobile BESS capacities by 2050. With much of this potential becoming available by 2030 through vehicle-to-grid (V2G) technology that enables EVs to be discharged back into the grid. This can meet the short-term grid needs.

V2G has potential, especially in correlation with the aggregation of EVs, which consequently enables their participation in energy markets [11-12]. As for now widespread use and implementation of V2G technology have several limitations, for example compatibility of charging stations (CSs) and EVs with bidirectional standards [13]. Currently, V2G demonstrations are limited to specific EV–charger pairings, with limited commercially available DC V2G CSs supporting all V2G-ready EVs [14-15]. This constrained interoperability has led to a strong focus on the EV–charger relationship, with less attention given to other critical infrastructures and actors required to enable EVs participation in flexibility services and, consequently, the development of energy markets [16].

Since bidirectional charging mass adoption is still limited, due to evolving standards (e.g., ISO 15118-20, OCPP), limited EV–CS compatibility, high hardware costs, regulatory uncertainty, and low user awareness, we are challenged to find alternatives for testing the flexibility potential of V2G EVs and their impact on the power grid, taking into account all relevant actors. A rigorous, data-driven assessment of EV flexibility under realistic operating conditions is therefore needed. Multi-actor demonstrators that enable real-world testing are a crucial step, as they serve as a bridge between technological developments and market adoption [17].

Considering the identified gaps, the main contribution of this paper is a novel methodology enabling the practical validation of V2G behaviour of multiple EVs by using a stationary BESS aggregated into a virtual power plant (VPP) to emulate their impact on the operational distribution grid and quantify V2G flexibility for multiple services. The approach combines statistical mobility data, historical grid load profiles, and market data to construct nine aggregated representative EV profiles defined for three use cases (UCs) employees EVs, company fleet and home charging, tailored to distinct flexibility services.

A multi-actor demonstrator with a stationary BESS that is aggregated in a commercial VPP was developed and deployed in an operational distribution grid in the city of Velenje, Slovenia. From a VPP point of view, an aggregated EV battery or a stationary BESS have similar properties, as both can store and release energy, while their availability differs. Because they also share the same measurement parameters, such as the state of charge (SOC) and battery capacity, we can treat aggregated EVs' batteries as a single BESS when considering the operation and scheduling of a VPP [18-19].

The combined charging and discharging behaviour of multiple EVs is emulated through developed aggregated representative EV profiles, that models' energy users in this case V2G EVs and consequently CSs. The aggregated representative EV profiles were demonstrated and consequently tested on a demonstrator, where they were uploaded to the VPP and activated on the BESS under operational distribution grid. By leveraging the developed aggregated representative EV profiles and testing on the operational distribution grid, the methodology enables robust assessment of technical performance, interoperability, quantification of flexibility potential, and flexibility services at the local and national levels. Additionally, findings advance understanding of EV flexibility for relevant stakeholders.

The paper is structured as follows: Section 2 reviews an overview of flexibility services enabled by mobile BESS. Section 3 introduces methodology that enables practical evaluation of V2G behaviour of multiple EVs using BESS aggregated into a VPP. Section 4 presents its application to the EVflex demonstrator. The tests included nine VPP activations of the BESS with selected EV profiles tailored to distinct flexibility services.

Section 5 provides details for the three selected VPP activations, focusing on an employee's UC and the provision of local flexibility services, manual frequency restoration reserve (mFRR), and automatic frequency restoration reserve (aFRR). Real-world measurements from the VPP, BESS, and secondary substation (SS) are used to evaluate system performance, quantification of V2G flexibility for multiple services and grid impact.

Section 6 provides a broader discussion of all nine activations, assessed through flexibility potential, number of flexibility services activations and three indices: *Flexibility*, *V2G_utilization* and *BESS_response* index. The findings advance understanding of V2G-supported EV flexibility for aggregators, charge point operators (CPOs), and distribution system operators (DSOs).

2. Overview of flexibility services enabled by mobile BESS

Flexibility serves as a key step in the green energy transition, as it ensures that power supply and demand are always in balance, even when new RES and loads are being added. Flexibility measures, such as demand-side management, adjustment of RES, balancing services, and local flexibility, are defined. Flexibility is provided to the power grid through the procurement and activation of flexibility services to mitigate congestion and voltage issues in distribution grids or frequency stability at system level. Such services are, for example, congestion management at the distribution level and mFRR and aFRR at system level [2]. Among the different sources of flexibility, BESSs are key enablers of flexibility owing to their rapid response capabilities [20], scalability, and suitability for energy market participation [6].

Flexibility is not only a technical challenge but is also closely linked to the energy market [21-22]. An innovative approach enabling EVs participation in energy markets is aggregation via a VPP managed by an aggregator, as presented in [23]. As an advanced energy management system, a VPP aggregates various distributed energy resources (DERs), such as solar and wind power plants, BESSs, EVs, and controllable loads, into a cohesive, cloud-based network [24]. This aggregation enables the VPP to operate as a single power plant capable of participating in energy markets and providing essential flexibility services [25-26]. Due to the stochastic behaviour of EVs, VPP's algorithm needs to be robust and aggregate higher proportion of EVs as required to ensure achievement of market requests in any situation [27]. From the VPP perspective, aggregated EV batteries and stationary BESS share similar characteristics, as both can store and discharge energy, differing mainly in their availability. Since they also share key measurement parameters, aggregated EV batteries can be represented as a single BESS for VPP operation and scheduling purposes [18-19]. Through VPPs, EVs could provide positive or negative flexibility on local or national markets, helping, DSOs and transmission system operators (TSOs) manage the growing impact of EV adoption [28-29]. The complex interactions between actors and components can be described with use case and smart grid architecture model (SGAM) methodologies, adopted to specific case, for example VPP [24]. EVs can provide positive flexibility by discharging or reducing their charging power, and negative flexibility by charging or increasing their charging power [11], [30]. These concepts are being tested in real-world demonstrators including EV4EU [11], EDISON [31], FENIX [32].

Recent research emphasizes the need for quantifiable metrics to assess energy system flexibility from both technical and operational perspectives. The Flexibility Index for distributed energy system introduced in [33] evaluates design-level adaptability under varying demand and supply conditions with considerations for economy, autonomy, energy efficiency, and environmental friendliness. Index with aggregators perspective is presented in [34], linked with flexibility. Expansion to e-mobility is presented in [35], proposing data-driven indices to assess EV charging flexibility and market interactions. Collectively, these works highlight the importance of standardized, multi-dimensional indices.

Despite its potential, V2G adoption faces technical and regulatory barriers. Many EVs and CS are not yet compatible with bidirectional standards such as ISO 15118-20 [13], while protocols such as the open charge point protocol (OCPP) are still evolving to support full V2G functionality [36]. Additionally, most V2G implementations in the EU rely on the combined charging system (CCS) protocol, which has only recently integrated bidirectional capabilities via ISO 15118-20, while outside EU, CHAdeMO protocol is also being use by Japanese manufacturers and serves as recommended national standard (GB/T) in China. V2G technology can also be used as an AC or DC. Unlike AC (IEC 61851-1), DC enables a more comprehensive data exchange between the EV and CS, providing CPOs with vehicle SOC and diagnostic information [37]. However, high hardware costs, unclear financial incentives, inconsistent regulations, and standardization across manufacturers hinder V2G investment, whereas low user awareness and battery concerns limit adoption [38]. Vehicle-to-everything (V2X) technologies, which are broader terms of V2G, are currently being tested in the EU V2X Cluster and projects integrated in BRIDGE [39].

Various methodologies have been explored for the development of EV profiles that emulate the behaviour of EV users and support the assessment of their impact on the power grid. The authors in [40] and [41] used data from 270 charge points to define EV profiles, respectively, based on clustering techniques. In [41], profiles also included the SOC at the plug-in and the desired SOC at the plug-out. A Markov chain model for forecasting CS occupancy was proposed by [42], whereas [43] introduced standard BESS profiles for different applications using a holistic simulation framework. In [44], the authors combined historical charging data with weather, traffic, and event data to predict EV session duration and energy consumption.

A representative profile method was introduced in [45], where it models the entire fleet by picking a subset of the vehicles and scaling their parameters related to battery capacity, rated charging power, consumption, etc. In addition, they also proposed a virtual battery approach that models the EV fleet as a single energy storage.

Demonstrators serve as bridge between technological development and market adoption. In [46] BESS was used for frequency regulation and energy trading, while participation in multiple services was modelled and experimentally tested in [47], confirming the role of BESS in providing flexibility services. V2G capabilities were explored in [48] and [49], presenting the development of EV emulators and reported the first real-world demonstrations of V2G responding to a frequency contingency. The [50] demonstrates the coordinated control of flexible assets, such as DC fast chargers, V2G EVs, and stationary BESS for the provision of congestion management.

3. BESS emulating V2G aggregation

Methodology for evaluating EV flexibility through emulation of V2G behaviour using a stationary BESS aggregated into a commercial VPP is presented in Section 3. We propose data-driven methodology for development of aggregated representative EV profiles derived directly from statistical data on mobility, grid load, and market conditions, explicitly considering V2G capabilities, as an extension of [45]. Our approach does not require individual profiles to construct aggregated one. The proposed novel methodology further enables the creation of EV profiles for diverse UCs, tailored to the provision of distinct flexibility services. Additionally, it enables practical validation of V2G behaviour to emulate impact of multiple EVs and quantify flexibility, by using BESS aggregated into a VPP.

In addition, this abstraction enables controlled and scalable testing of flexibility services without requiring direct physical connection to multiple EVs, while preserving the essential dynamics of V2G behaviour. The high-level steps of the proposed methodology from development of aggregated representative EV profiles to the testing on the demonstrator are presented in Figure 1. The first three steps, related to the development of aggregated representative EV profiles, are described in Section 3.1, while Section 3.2 presents the testing procedure and analysis on the demonstrator.

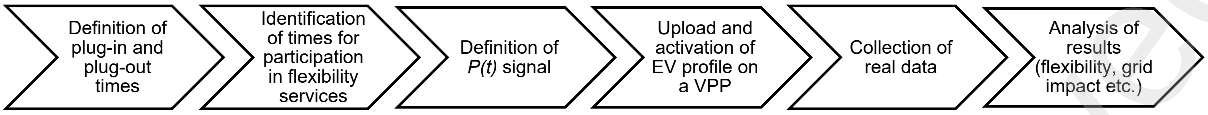


Figure 1: Main steps of the proposed methodology

3.1 Input data and methodology for development of aggregated representative EV profiles

The proposed aggregated representative EV profiles are defined using statistical mobility data, historical grid load measurements, and market specific data. Determination of plug-in and plug-out times of aggregated representative EV profile is based on statistical data on vehicle users' behaviour, more specifically statistical data on the probability of the start of vehicle journeys, for different purposes. Analysed statistical data are used to derive probability distributions of hours vehicles start their movements, which inform the arrival (t_a) and departure times (t_d) of individual EVs. These are aggregated to define the average connection time (t_{a_agg}, t_{d_agg}) of the aggregated representative EV profile for selected UC. The methodology for definition of plug-in and plug-out times of aggregated representative EV profiles is presented in Figure 2a.

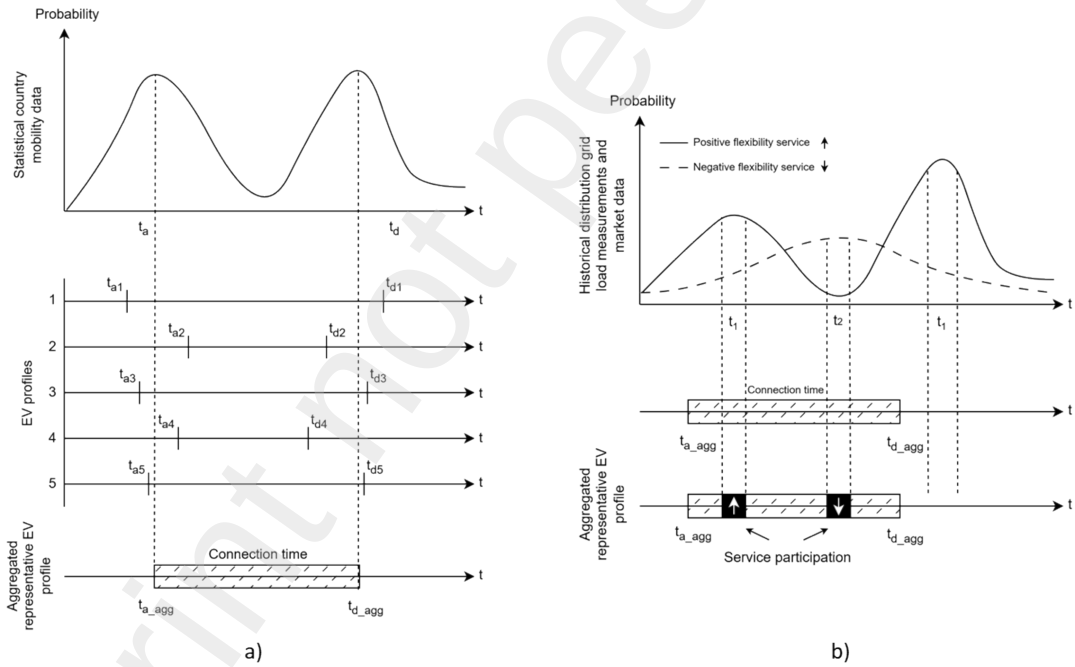


Figure 2: Methodology for determine plug-in and plug-out times of aggregated representative EV profiles, based on statistical data on vehicle users' behaviour (a). Concept for identifying flexibility services activation times based on historical distribution grid load measurements and balancing market data (b).

In our approach flexibility services activation times are based on historical distribution grid load measurements and market data. Distribution grid load data are used to identify peak load periods and high-probability time windows when activation of certain local flexibility service is most needed. To identify time windows with the highest probability that the request for the activation of balancing service will occur, data including activation patterns and historical occurrences of balancing services are needed from the market operator. High-probability time windows for service requests are compared with the connection time of an aggregated representative EV profile, enabling the selection of feasible periods for participation in flexibility services. The concept is presented in Figure 2b.

EV battery behaviour models, determine the SOC at plug-in and plug-out, as well as charging and discharging constraints. These may also rely on empirical data, manufacturer specifications, or optimization strategies to preserve battery health.

Once the plug-in and plug-out times, SOC at plug-in, target SOC at plug-out, and feasible time windows for flexibility services provision are defined, the next step is to define power as a function of time signal (*P(t)*) for the selected EV profile. This signal defines the time interval and charging or discharging power of the emulated EVs A visual description of *P(t)* signal definition is presented in Figure 3. *P(t)* signal is defined to, either provide flexibility services or to reach the desired SOC at plug-out. As a central element of the EV profile, *P(t)* is uploaded to the VPP and consequently activated on the BESS. Each EV profile corresponds to a defined set of emulated aggregated V2G CSs with selected rated power.

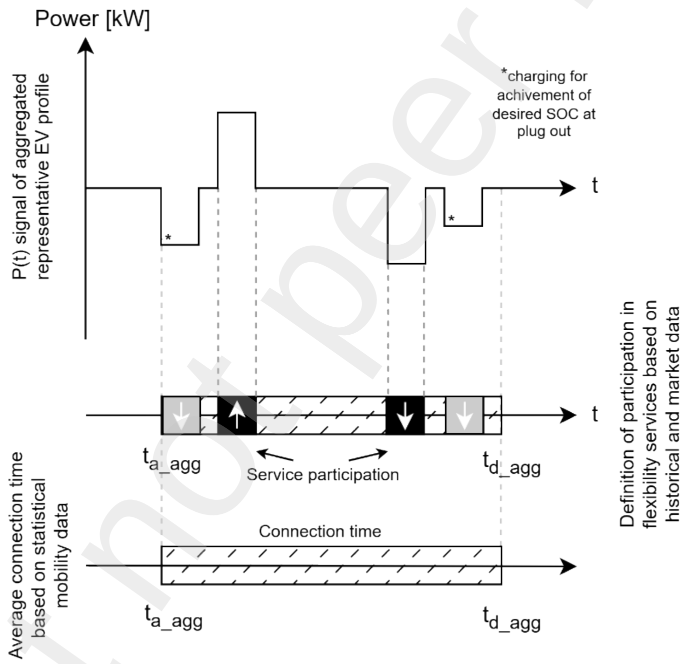


Figure 3: Definition of P(t) signal - time-varying charging (negative values) and discharging (positive values) power - for the aggregated representative EV profile based on connection time, feasible timeslots for participation in flexibility services and required SOC at the end of activation.

3.2 Demonstrator specification with proposed testing procedure

To evaluate the proposed approach, the demonstrator with BESS aggregated to the commercial VPP is required. Additionally, the BESS is connected to the operational distribution grid, to provide the real-world data and consequently relevant conclusions.

Since the proposed approach is also tested on a demonstrator, it enables scalable and realistic representation of the collective impact of emulated V2G-enabled EVs on the power grid, facilitating accurate quantification of their flexibility potential and providing valuable insights for stakeholders in designing flexibility strategies and optimising resource allocation.

For the VPP activation of the aggregated representative EV profile on the BESS, activation parameters should be reached such as the correct activation start time and the SOC of the BESS that aligns with the defined EV profile, and consequently, its UC. Once the activation parameters are reached and the activation signal, which is equal to the *P(t)* signal of the EV profile, is uploaded to the VPP, activation is performed; this is called the activation procedure.

Real-time data is monitored by both VPP and DSO. After activation, data from VPP and BESS should be collected, including power signals and SOC, which are ready for analysis. Additionally, grid measurements are collected from the SS to assess the grid impact. The analysis verifies whether the BESS accurately followed the VPP activation signal within predefined response time and evaluates the success of flexibility services provision, using power grid data and VPP measurements.

Three indices were designed to evaluate actors' perspectives, capturing BESS response accuracy, total activated flexibility, and V2G utilization. The *BESS_response* index evaluates how accurately the BESS follows the activation signal from the VPP and is particularly relevant for the aggregator and consequently CPO. The *Flexibility* index quantifies the total amount of activated flexibility to the distribution grid for the provision of selected flexibility services in the scope of chosen VPP activation The percentage of V2G used in the activations of selected flexibility service is presented with the *V2G_utilization* index, relevant for the aggregator and consequently DSO.

BESS_response index is calculated as a ratio between $E_{response}$, energy provided by BESS during the activation and $E_{requested}$, requested energy from the VPP:

$$BESS\_response_{index} = \frac{E_{responded}}{E_{requested}} [\%] \quad (1)$$

Flexibility index combines the sum of activated negative and positive flexibility for selected VPP activation of EV profile:

$$Flexibility_{index} = \sum E_{neg\_flex} + \sum E_{pos\_flex} \, [kWh] \quad (2)$$

V2G_utilization index is defined as a ratio of a sum of $E_{pos\_flex.}$, the total positive flexibility activated during one VPP activation of selected EV profile and *Flexibility* index:

$$V2G\_utilization_{index} = \frac{\sum E_{pos\_flex.}}{Flexibility_{index}} [\%] \quad (3)$$

4. Application of the methodology to the demonstrator

Section 4 provides the application of our proposed methodology to the EVflex demonstrator, where BESS is aggregated into a commercial VPP, connected to the operational distribution grid. In Section 4.1 specific data from Slovenia are outlined, while in Section 4.2 nine developed aggregated representative EV profiles for three different UCs tailored to distinct flexibility services are presented. Section 4.3 provides the specifications and testing procedure for the demonstrator.

4.1 Data specification

To define aggregated representative EV profiles for selected UCs relevant to Slovenia, we utilized data on personal vehicle user behaviour provided by the Statistical Office of the Republic of Slovenia [51], historical distribution grid load data from the Slovenian DSO [52], and Slovenian balancing market data [53]. Trip start probabilities for activities classified as work and leisure were derived from statistical analyses [51]. We assumed that all vehicles finish their journey within the same hour as they started it. Statistically, this applies to 94 % of the routes [51]. The SOC at plug-in and plug-out was defined based on characterization of EV charging modes presented in [41], considering optimal battery usage based on [54].

Grid conditions were modelled using historical grid load data from [52], with peak load hours adjusted to reflect current weekday and weekend patterns to identify high-probability time windows for the need for local flexibility services activations. Activation patterns and historical occurrences of balancing services from Slovenian balancing market data [53] were analysed to identify time windows with the highest probability of mFRR and aFRR activations requests.

4.2 Developed aggregated representative EV profiles

Based on the proposed methodology in Section 3.1 we have developed nine aggregated representative EV profiles relevant for Slovenia. EV profiles were developed for three UCs, presenting EV charging at home and at work during the workday. Furthermore, work UC is divided into employees' EVs and company EV fleet. Meaning that in this study we analyse developed EV profiles related to *UC_home*, *UC_employees'* and *UC_EVfleet*.

The *UC_employees'*, assumes that the emulated EVs are plugged in at 8.00 and unplugged at 16.00, that corresponds to average working hours in Slovenia. The SOC at the plug-in was 40% and the required SOC at the plug-out was 80%. The *UC_home* assumes that EVs are plugged in at 16.00 and unplugged at 8.00 next day, while the SOC at plug-in was 40% and the required SOC at the plug-out was 80%. The plug-in and plug-out hours are the same for the *UC_EVfleet*, where the SOC at the plug-in was 20% and the required SOC at the plug-out was 90%. For every UC three aggregated representative EV profiles for participation in selected flexibility services were developed.

The aggregated representative EV profiles emulate five aggregated CSs with connected V2G supported EVs. Each CSs had a power of 8 kW; thus, the total maximum charging or discharging power of the emulated aggregated CSs was 40 kW.

We developed three aggregated representative EV profiles that represent EVs participation in local flexibility services such as congestion management. Another six EV profiles were developed for participation in the balancing market, particularly for aFRR and mFRR. The nine aggregated representative EV profiles and the corresponding *P(t)* signals are presented in Figure 4.

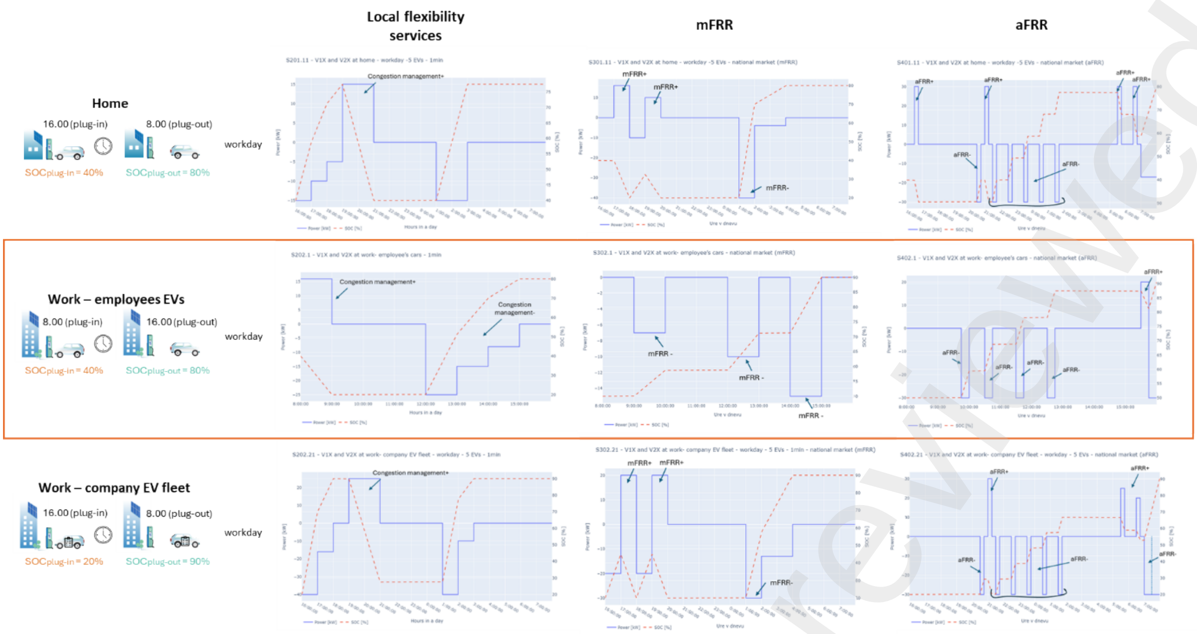


Figure 4: Developed aggregated representative EV profiles and corresponding P(t) signals for participation in local flexibility services, mFRR, and aFRR for UC_home. UC_employees' and UC_EVfleet, relevant for Slovenia. Where blue lines present power and dotted red, SOC.

The three aggregated representative EV profiles related to *UC_employees'*, whose VPP activations on BESS are analysed in detail in this study (Section 5), are shown in Figure 4. Additionally, developed EV profiles for *UC_home* and *UC_EVfleet* are also presented in Figure 4 where evaluation and analysis process are similar as presented in Section 5. Results of aforementioned UCs are discussed in Section 6.

4.3 Demonstrator setup and testing procedure

Demonstrator setup and testing approach on which nine developed EV profiles (Section 4.2) were tested is presented in Section 4.3. The demonstrator was designed with a focus on operational technologies, including the use of a commercial VPP and testing under operational grid conditions. As a result, all components of the demonstrator are industry-grade and prepared for commercial deployment once LFM is active. While the system is capable of aggregating any number of BESSs or CSs, such scalability is not in the scope of this study.

Following the approaches in [24] and [55] where authors adapted the SGAM framework to their respective research contexts, the component and business layers for the EVflex demonstrator are illustrated in Figure 5 and Figure 6. This paper focuses on these two layers, as its scope lies within the flexibility domain.

From Figure 5 it can be observed that the BESS with 80 kWh capacity and 40 kW rated charging or discharging power is managed and fully controlled by the energy management system (EMS). The EMS communicates with the VPP, which aggregates the BESS into its portfolio. When the activation of the BESS is required, the VPP sends the power setpoint to the EMS of the BESS, which then charges or discharges the BESS based on the received setpoint. It can be further observed that the BESS is connected to the low voltage side of the SS with a rated power of 630 kVA, located in the city of Velenje. The SS has seventeen business consumers and four solar power plants (PVs) with a rated power of 198 kWp. The SS was monitored by the DSO's backend system. On Figure 5 and Figure 6 is also illustrated full demonstrator incorporated in LFM, which is out of the scope of this paper.

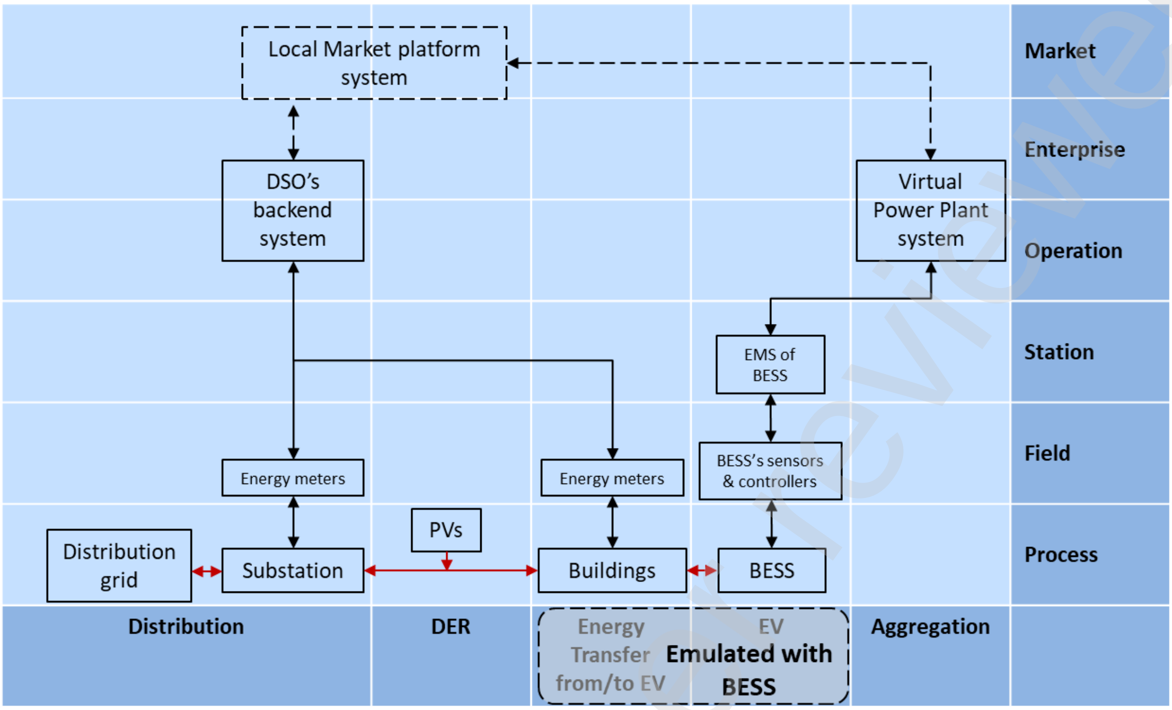


Figure 5: Component layer illustration of the demonstrator with BESS aggregated via VPP integrated in operational distribution grid, following the modified SGAM component layer structure. The dashed components are part of the full demonstrator incorporated in LFM.

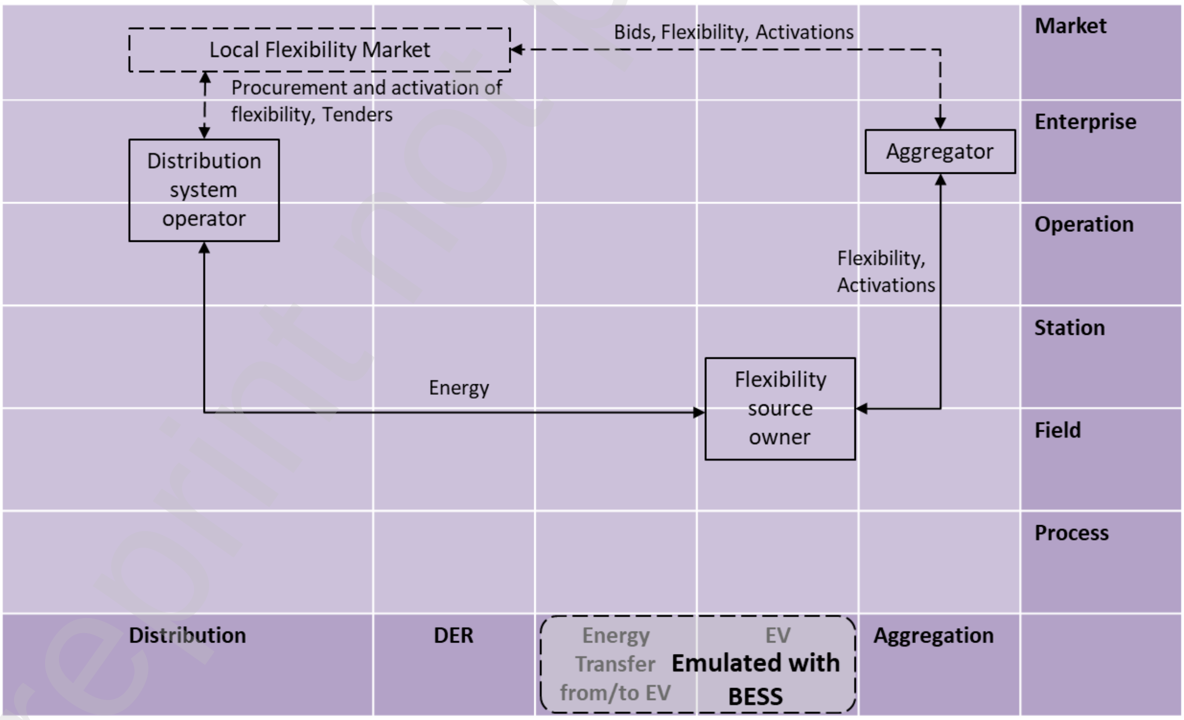
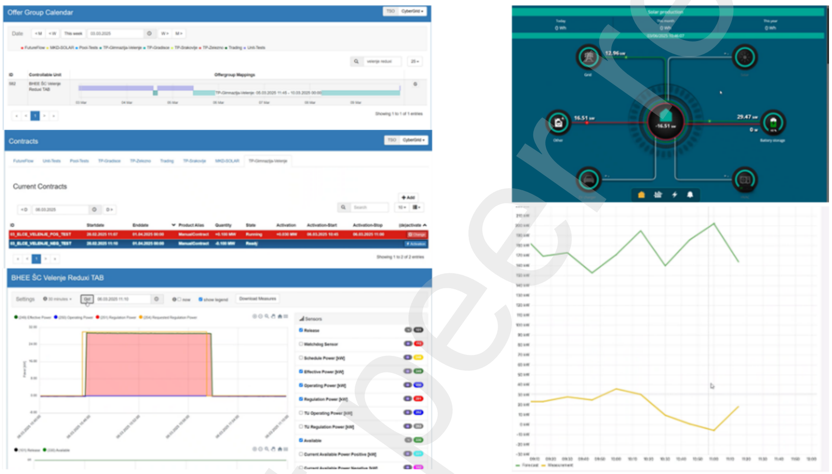


Figure 6: Activation procedure illustration for the EVflex demonstrator following the modified SGAM business layer structure. The dashed components are part of the full demonstrator incorporated in LFM.

In the first step of the activation procedure (Figure 6), the aggregated representative EV profile is uploaded to the VPP, which is operated by the Aggregator. After the activation parameters are met, the EV profile – and consequently its *P(t)*—is activated on the BESS, which is owned by the flexibility source owner. During activation, the DSO monitors the parameters.

After each activation, data were collected from the VPP and BESS, including activation signals, flexibility measurements, and BESS parameters such as effective power, requested power and SOC. The VPP perspective during and after activation is shown in Figure 7a. To assess the grid impact, additional measurements of active power, reactive power, and voltage, were obtained from the SS operated by the Slovenian DSO. The perspective of the DSO is shown in Figure 7b. Presented measurements relevant for selected VPP activations were used for the analysis and evaluations in Sections 5 and 6.

Aggregator (VPP) DSO (secondary substation)



a) b)

Figure 7: VPP activation from VPP and DSO operators' view. a) Presents the real-time monitoring data that the VPP operator can see during flexibility service activation and operation. b) Shows the real-time data from the SS available to the DSO operator.

Testing of VPP activations on BESS was performed during the distribution grid in operation. Hence, the reason for the impact on the SS conditions may not be solely due to the charging or discharging of the BESS, but it certainly has a distinct impact. The analysis and evaluation of the selected VPP activations are presented in Section 5.

5. Selected VPP activations results of aggregated representative EV profiles

Three different VPP activations of aggregated representative EV profiles for the *UC_employees'*, related to the participation in flexibility service (Figure 4) are analysed and evaluated in Section 5. The first selected activation focuses on provision of local flexibility service, more specifically congestion management (Section 5.1), whereas the other two VPP activations focus on provision of mFRR (Section 5.2) and aFRR (Section 5.3) services, all related to the *UC_employees'*.

5.1 Participation in local flexibility services

Section 5.1 focuses on the analysis of the VPP activation results for the provision of local flexibility service, congestion management for the *UC_employees'*. To analyse VPP activation and its success, we analysed measurements from VPP and, consequently from BESS and selected SS.

To assess whether the BESS responded correctly to the requested setpoint of VPP activation signal, we analyse the measurements from the VPP and BESS. Figure 8 shows the measurements from the VPP and BESS. The red line represents the VPP activation signal sent by the VPP, whereas the blue line represents the power response of the BESS. Negative values represent charging, and the positive values represent discharge.

From Figure 8 it is evident that the power response of the BESS correctly followed the power setpoint sent by the VPP through the activation signal. We can conclude that the activation was successful if we consider the VPP and BESS measurements. The accuracy of the BESS response on the VPP activation signal, and therefore, the *BESS_response* index was 97%. From Figure 8 it is also evident that the BESS was charged to 84% of the SOC at the end of activation, which is less than the expected 90%, due to BESS's self-consumption and losses. However, Figure 8 shows that despite participation in the flexibility services, the BESS and consequently emulated EVs were all charged nearly to the desired SOC at plug-out.

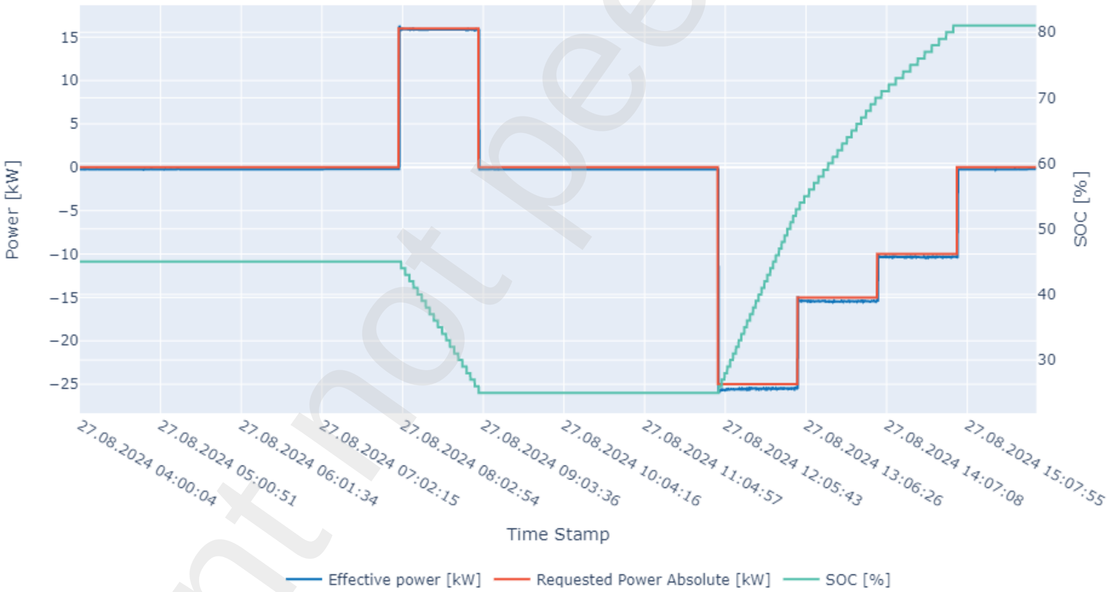


Figure 8: VPP measurements for activation signal of EV profile related to UC_employees' for participation in local flexibility services. The red line represents the VPP activation signal sent by the VPP to BESS. The blue line represents the power response of the BESS (positive numbers represent discharging, while negative numbers represent charging), and the green line represents the SOC of the BESS during activation.

To assess whether participation in local flexibility services was successful, we analysed the measurements from the SS in combination with the data from the VPP for the observed period. A visualization of the measurements from the SS and the VPP is shown in Figure 9. The dashed blue line represents BESS's response to the VPP activation signal.

On the SS, separate channels record consumption, represented with active (A+) and reactive (R+) power and excess production or energy imported to the grid (A−, R-). Since measurements are aggregated in 15-minute intervals, both values can appear simultaneously.

The *congestion management+* marked rectangle in Figure 9 represents the provision of positive congestion management service. The congestion management service with provision of positive flexibility was activated when a peak load was expected in the selected SS. As already mentioned in Section 3, the expected time of the peak load and therefore activation of the flexibility service was defined based on analysis of statistical data, consequently, the observability for service activation was not in real time.

The load of the SS (A+) decreases when the positive congestion management service is activated, indicating that the activation of selected congestion management was successful. The reason for the decrease in substation load may not be solely due to the discharge of the BESS, but it certainly has an impact. The dotted line of the SS load represents the illustrated load without BESS activation, indicating the estimated impact of the BESS on SS conditions. In our case, the BESS had no notable impact on reactive power, therefore its effect is not further addressed.

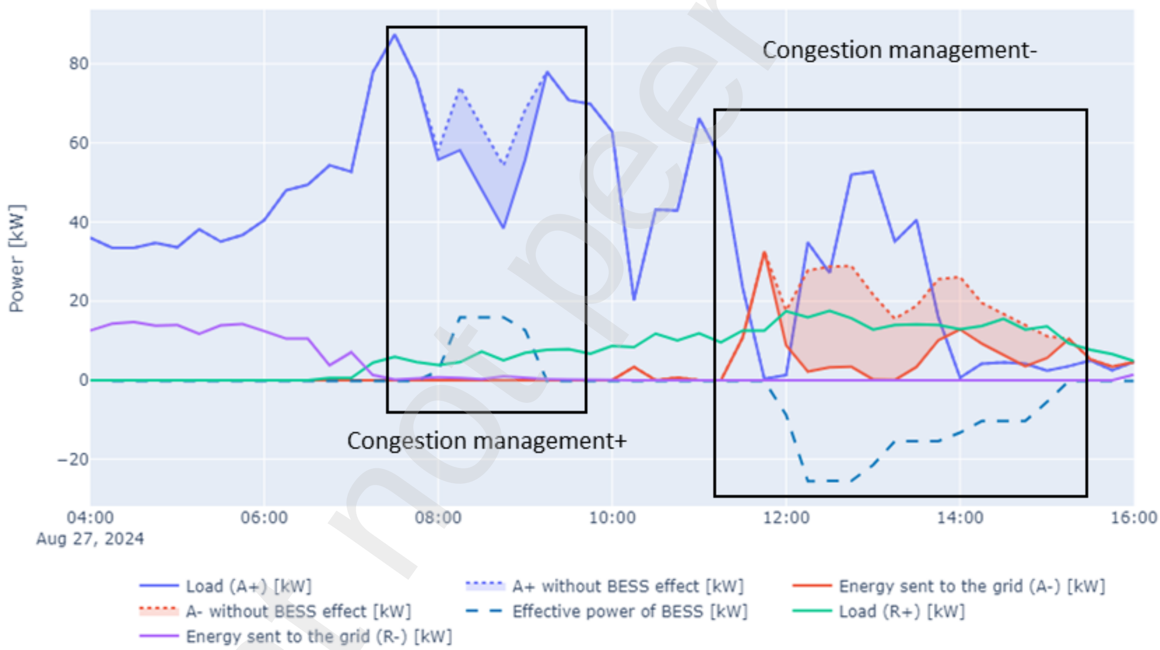


Figure 9: Measurements of active and reactive power at selected secondary substation for VPP activation signal of EV profile related to UC_employees' for participation in local flexibility services. The blue line (A+) represents the load, and the red line (A-) represents the excess active power sent to the grid by the PVs. The reactive power used from the grid is presented with green (R+), and the reactive power sent to the grid is shown in violet (R-). Dashed blue line represents BESS response on VPP activation signal.

Provision of the congestion management service with activation of negative flexibility is marked in Figure 9 with *congestion management-* rectangle. The BESS starts charging after 12.00 with the aim of using the expected PV excess production and thus stabilising the energy grid as PV excess production will decrease. In addition, the BESS was charged with green energy.

From Figure 9 it can be observed that the red line (A-), which represents the excess PV production at the SS, decreases when charging starts. The estimated impact of the BESS's provision of negative congestion management on SS is illustrated by the highlighted area between the dotted and solid red lines. We can conclude that the activation of the negative congestion management service was successful, as it had the effect on decreasing the excess PV production and consequently energy imported to the grid during the observed period.

5.2 Participation in mFRR

The analysis results of the VPP activation signal of *UC_employees'* for participation in balancing services, more accurately in mFRR, are presented in Section 5.2.

From Figure 10 we can observe that the power response of the BESS correctly followed the activation signal and consequently requested the setpoints sent by the VPP. Therefore, we can conclude that selected VPP activation was successful when VPP and BESS measurements were considered. *BESS_response* index was 91%.

The response time of the BESS was very fast, which is crucial for the provision of balancing services. In our case, the response time of BESS to the VPP activation signal was approximately 20s (Figure 10). The reason is that the VPP first sends an activation signal to the EMS of the BESS, and then the EMS analyse the signal and sends the power setpoint to the BESS to which it responds.

Despite participation in the mFRR service, the BESS was charged to the desired SOC at plug out, as can be seen in Figure 10. This means that, in our case, the provision of mFRR services has no negative impact on achieving the desired SOC.

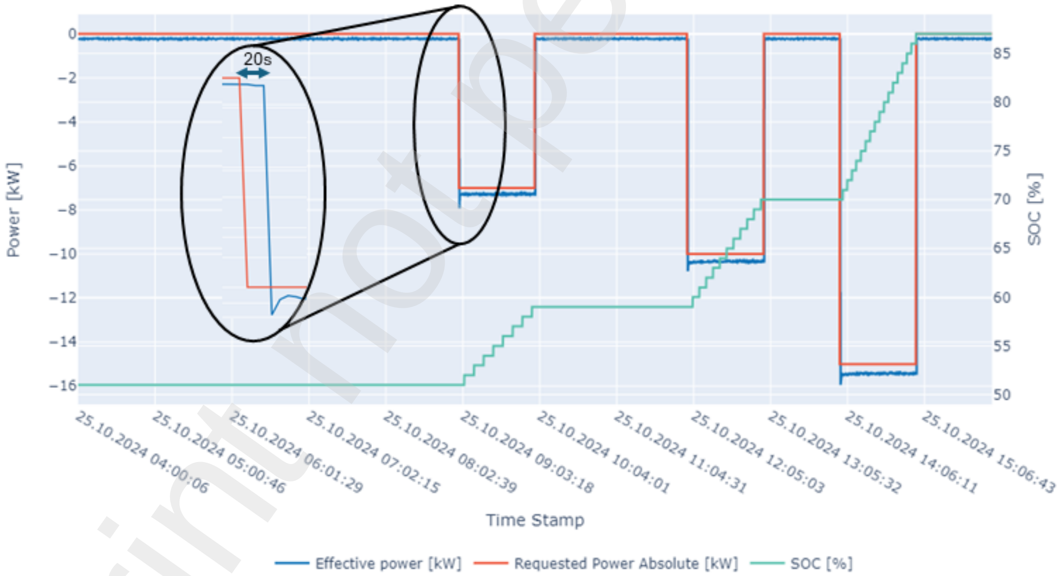


Figure 10: VPP measurements for activation signal of EV profile related to UC_employees' for participation in mFRR. Red line represents VPP activation signal sent by VPP to BESS. Blue line represents the power response of BESS (positive numbers presents discharging, while negative presents charging), green line represents SOC of BESS during activation.

The measurements from the SS and the VPP are visualized in Figure 11, which serve to estimate the success of the mFRR activations and its impact on the selected power grid. The marked *mFRR-*rectangles in Figure 11 indicate provision of negative mFRR services. It is evident that in the selected VPP activation, only participation in negative mFRR services occurs. This is because, based on the statistical analysis there is no high probability that a request for a positive mFRR service will occur in the observed period.

Participation in the negative mFRR between 9:00 and 10:00 had the most negative effect on the stability of the selected SS. One of the reasons is that the peak load on the SS, which is expected between these hours, is additionally increased owing to the BESS charging.

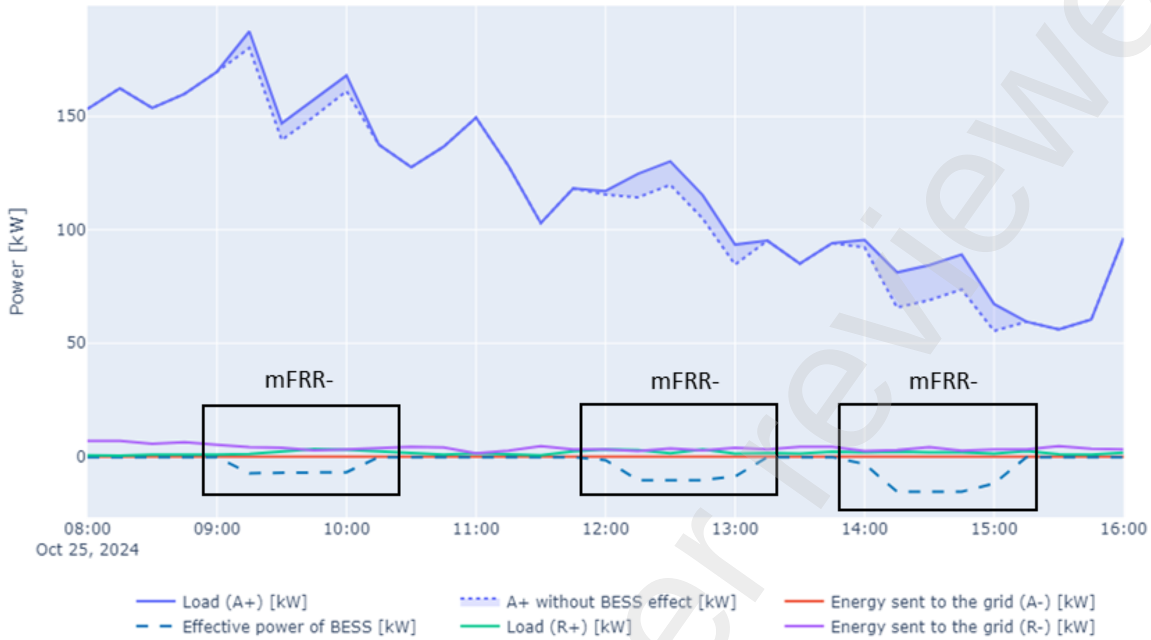


Figure 11: Measurements of active and reactive power at selected secondary substation for VPP activation signal of EV profile related to UC_employees' for participation in mFRR. Blue line (A+) presents the load, where red line (A-) presents excess active power sent to the grid by PVs. Reactive power used from the grid is presented with green colour (R+), reactive power sent to the grid is shown with violet (R-). Dashed blue line represents BESS response on VPP activation signal.

The other two mFRR participations did not have such a negative impact on the condition in the selected SS, as it is underloaded during the activation hours. Participation in the mFRR between 12:00-13:00 and 14:00-15:00 not only contributes to stabilization of the power grid at the system level, but it also has the potential to enhance stability of the local distribution grid, since PV excess production is expected.

5.3 Participation in aFRR

In Section 5.3, we focus on the analysis of VPP activation results of EV profile related to *UC_employees'* for participation in aFRR services. The measurements from the VPP and BESS for the selected activation are shown in Figure 12. The BESS (marked in blue) correctly follows the activation signal sent by the VPP (marked in red). Based on the collected measurements, we concluded that the *BESS_response* index was 94%.

The response of the BESS to the power change was fast and accurate, which is crucial for participation in aFRR balancing services. The length of a given charging or discharging activation interval was 15min, which is in line with the requirements for participation in the aFRR service in the Slovenian balancing market [53].

Despite the provision of the aFRR service, the desired SOC at plug-out was achieved, as shown in Figure 12. We can conclude that, in this case, the achievement of the desired SOC was not negatively affected, despite participation in balancing services.

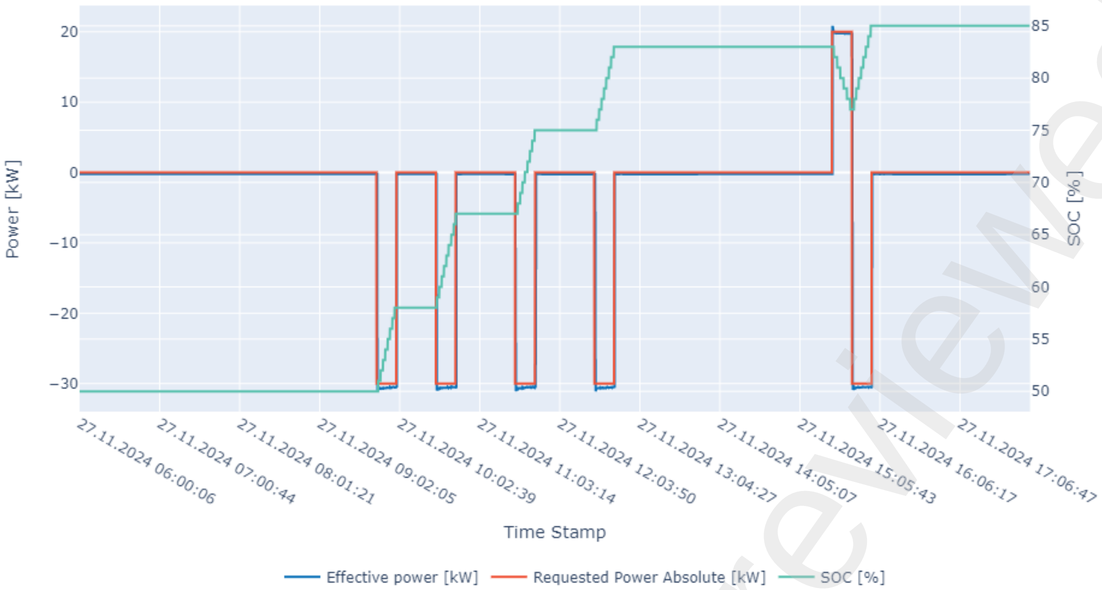


Figure 12: VPP measurements for activation signal of EV profile related to UC_employees' for participation in aFRR. Red line represents VPP activation signal sent by VPP to BESS. Blue line represents the power response of BESS (positive numbers presents discharging, while negative presents charging), green line represents SOC of BESS during activation.

The measurements from the SS and VPP are in Figure 13. The *aFRR-* marked rectangle in Figure 13 presents provision of negative aFRR services. However, the *aFRR+* rectangle represents provision of positive aFRR service during which the BESS is discharging. It is evident that, in aFRR, participation in positive balancing services also occurs, which is not the case in mFRR (Section 5.2).

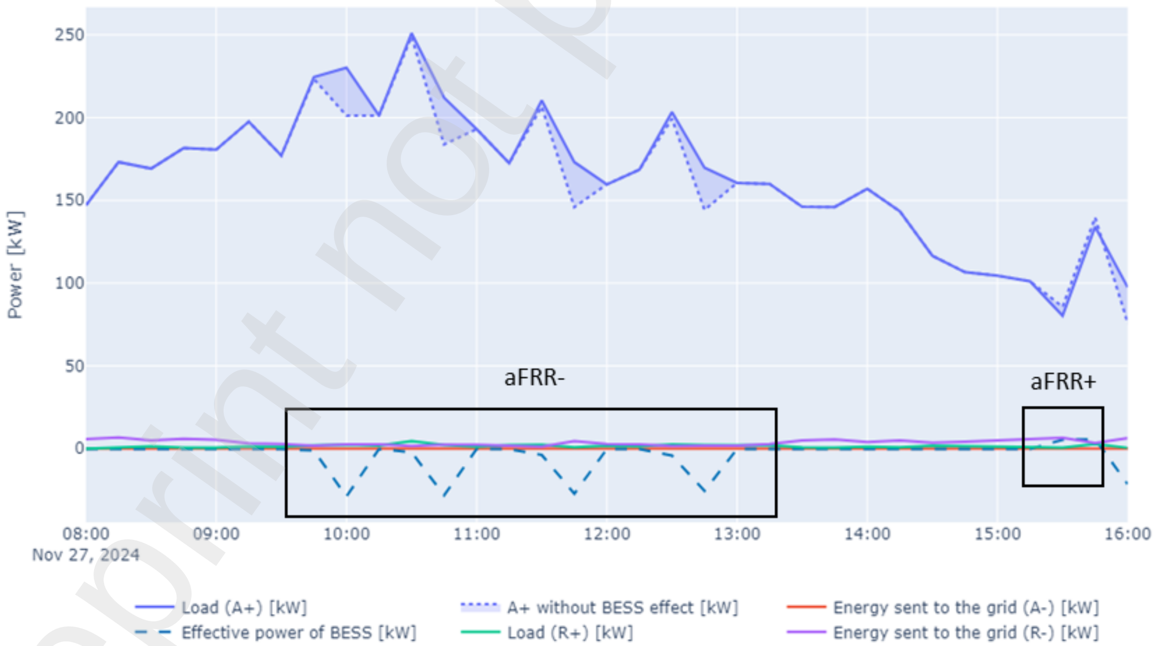


Figure 13: Measurements of active and reactive power at selected secondary substation for VPP activation signal of EV profile related to UC_employees' for participation in aFRR. Blue line (A+) represents the load, where red line (A-) represents excess active power sent to the grid by PVs. Reactive power used from the grid is represented with green colour (R+), reactive power sent to the grid is shown with violet (R-). Dashed blue line represents BESS response on VPP activation signal.

Participation in a negative aFRR at 10:00 may have negatively affected the conditions in the selected SS because it coincided with the expected peak load. BESS charging at that time, and thus, its participation in the aFRR could further increase the substation load. In contrast, other negative aFRR activations did not significantly affect the local grid stability.

The services that are activated at 12:00 and 13:00 not only contribute to the stabilisation of the grid at the system level but also could have a positive impact on the conditions in the local grid. During these hours, excess PV production was expected. In the aforementioned period, the excess PV production is not visible.

During the time the BESS was discharging for provision of positive aFRR service, the load at the SS decreased, meaning that participation in the balancing market also had a positive effect on the conditions on the local grid, alongside the grid at system level.

The last charging is not part of the participation in the aFRR service but serves to achieve the desired SOC at the plug-out. It is evident that this does not have a major impact on the stability of the selected SS.

6. Quantification of V2G flexibility for multiple services and UCs

The discussion section is structured around key findings from the conducted VPP activations. It first examines the quantity and type of flexibility contributions across different UCs and services, followed by an evaluation based on three defined indices: *Flexibility* Index, *V2G_utilization* Index, and *BESS_response* Index. Finally, it addresses the impact of balancing services on local grid conditions and reflects on the overall performance and technical operability of the demonstrator.

Table 1 presents flexibility quantification comparison of VPP activations for three different UCs *UC_home*, *UC_employees' and UC_EVfleet*, regarding participation in local flexibility services, mFRR and aFRR. Assessed through activated flexibility and number of flexibility services activations.

Table 1 shows that the highest number of flexibility activations occurred in aFRR, followed by mFRR and local flexibility services. This is primarily due to the longer activation durations of local services, resulting in fewer total events. The *UC_employees'* provided the highest amount of negative flexibility (48 kWh) in local services, while the *UC_home* contributed 40 kWh in mFRR, and the *UC_EVfleet* delivered the highest overall negative flexibility with 52.5 kWh in aFRR. Regarding positive flexibility, the *UC_EVfleet* contributed the largest amount in local flexibility services (50 kWh) and mFRR (40 kWh), while the *UC_home* provided the highest value in aFRR with 45 kWh.

Table 1: Flexibility quantification comparison of VPP activations for three different UCs, regarding participation in local flexibility services, mFRR and aFRR

	UC	Participation in local flexibility services	Participation in mFRR	Participation in aFRR
Number of flexibility services activations	*UC_home*	1	3	10
	UC_employees'	2	3	5
	UC_EVfleet	1	3	10
Activated negative flexibility [kWh]	*UC_home*	0	40	30
	UC_employees'	48	32	30

	UC_EVfleet	0	30	52.5
Activated positive flexibility [kWh]	*UC_home*	30	26	45
	UC_employees'	16	0	5
	UC_EVfleet	50	40	18.75

These results suggest that aggregators should prioritize sources with high negative flexibility potential for local flexibility services and those with high positive flexibility potential for balancing services. Given the small-scale nature of our tests, the influence of aggregator and DSO perspectives on broader market participation remains limited, yet the results provide valuable insights.

Table 2 presents the results for the three indices for selected UCs participating in local flexibility services, mFRR, and aFRR, reflecting different actor perspectives in evaluating the demonstration. The highest total amount of flexibility was activated during participation in aFRR for the *UC_home* (75 kWh); therefore, the *Flexibility* index was 75 kWh. The highest *Flexibility* index in mFRR (70 kWh) was recorded for the EV fleet UC, while the *UC_employees'* had the highest index in local flexibility services. Therefore, from a flexibility potential perspective, the most suitable UCs are employees' for local services, EV fleet for mFRR, and home for aFRR.

Table 2: Comparison of indices for three different UCs regarding participation in local flexibility services, mFRR and aFRR

	UC	Participation in local flexibility services	Participation in mFRR	Participation in aFRR
Flexibility index [kWh]	*UC_home*	30	66	75
	UC_employees'	64	32	35
	UC_EVfleet	50	70	71.25
BESS_response index [%]	*UC_home*	96.95	91.28	94.24
	UC_employees'	96.18	96.35	96.96
	UC_EVfleet	98.75	97.49	97.15
V2G_utilization index [%]	*UC_home*	100	39	40
	UC_employees'	25	0	14
	UC_EVfleet	100	55	26

In the scope of local flexibility services, the *V2G_utilization* index reached 100% for both the *UC_home* and *UC_EVfleet*, indicating need only for activation of positive flexibility that was fully delivered via V2G emulation. This represents the high utilization potential of the V2G technology in specific UCs, which is relevant for aggregators and DSOs. In mFRR, the *UC_EVfleet* showed the highest V2G utilization at 55%, while the *UC_employees'* did not use V2G at all (0%). In aFRR, the *UC_home* had the highest *V2G_utilization* index of 40%, followed by the *UC_EVfleet*. Overall, the *UC_home* and *UC_EVfleet* show the highest V2G potential for local services, the *UC_EVfleet* is most promising for mFRR, and the *UC_home* for aFRR participation.

Findings from Sections 5.2 and 5.3 indicate that while participation in balancing services supports system-level grid stability, it can negatively impact local distribution grid conditions if not aligned with local load patterns. Therefore, the service activation should consider the expected local grid conditions. Introduction of the traffic light system (TLS) [56] is needed, which informs TSO about the local grid conditions and consequently influences balancing services activation decisions. However, certain mFRR and aFRR activations also have the potential to enhance stability of the local distribution grid, demonstrating that provision of balancing services can, in some cases, provide both balancing and local flexibility services at the same time.

Selected VPP activations show minor SOC deviations due to neglecting BESS efficiency, highlighting a point for future improvement. The average *BESS_response* index across all nine VPP activations was approximately 96%, confirming the high technical operability of the demonstrator.

7. Conclusion

This paper responds to the current lack of V2G infrastructure availability by proposing a data-driven methodology, enabling practical validation of V2G behaviour of EVs by using a BESS aggregated into a VPP. The proposed approach facilitates emulating their impact on the operational distribution grid and quantifying V2G flexibility for multiple services.

The approach combines statistical mobility data, historical grid load profiles, and market data to construct aggregated representative EV profiles defined for UCs tailored to distinct flexibility services. By leveraging the developed aggregated representative EV profiles and testing on the operational distribution grid, the methodology enables robust assessment of technical performance, interoperability, flexibility potential, and flexibility services at local and national levels.

The tests in the EVflex multi-actor demonstrator, included nine VPP activations, for the three UCs *UC_home*, *UC_employees' and UC_EVfleet* tailored for the provision of local and balancing services, using developed aggregated representative EV profiles. Selected three activations linked with *UC_employees'* for the provision of local flexibility services, mFRR, and aFRR were analysed in depth. Measurements from the VPP, BESS, and SS were analysed to evaluate the flexibility potential for participation in local and balancing services. The impact on the distribution grid was also assessed. Since VPP activations were tested on distribution grid under operation, the influence of BESS on SS load cannot be fully isolated, but its effect is evident.

In the discussion part, all nine VPP activations of selected aggregated representative EV profiles were evaluated based on flexibility potential, number of flexibility services activations and three indices: *Flexibility* index, *V2G_utilization* index and *BESS_response* index.

The results show that flexibility contributions differ by UC and flexibility service type: *UC_employees'* provided the highest amount of negative flexibility for local services, *UC_EVfleet* for aFRR, and *UC_home* for mFRR. In terms of positive flexibility, *UC_EVfleet* activated the highest value of flexibility in local and mFRR, while *UC_home* recorded the peak contribution in aFRR. Findings indicate that aggregators should prioritise UCs with high negative flexibility potential for local services and high positive flexibility potential for participation in balancing services. Based on the *Flexibility* index, *UC_employees'* provide the highest overall flexibility potential for local services, while *UC_EVfleet* for mFRR, and *UC_home* for aFRR. The insights advance the understanding of EV flexibility that V2G enables for aggregators, CPOs and consequently DSOs related to strategies, service matching and resource allocation.

Evaluation of indices linked to stakeholders, revealed that the *V2G_utilization* index reached 100% for the home and EV fleet UCs in provision of local services, highlighting their strong V2G potential.

UC_EVfleet showed highest V2G utilization in mFRR (55%), while *UC_home* provided highest in aFRR (40%). These findings confirm that UC and flexibility service pairing can optimize V2G utilization, offering actionable insights for aggregators, CPOs and DSOs. Balancing service participation can support stabilizing grid at system level but may negatively impact local grids if not aligned with local load conditions. Yet, specific aFRR and mFRR activations also have potential to improve local grid stability, showing possibilities for dual service provision.

Additionally, the communication between actors was tested and assessed. An average *BESS_response* index of 96% across nine VPP activations confirms the demonstrator's high technical performance.

For aggregators and DSOs, the findings provide valuable insight into how to strategically match flexibility sources with appropriate flexibility services, prioritize UCs based on their characteristics, and guide the future integration of V2G technology into energy markets.

References

[1] European Comission, "The European Green Deal," 2024.

[2] P. D. Lund, J. Lindgren, J. Mikkola and J. Salpakari, "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renewable and Sustainable Energy Reviews,* vol. 45, pp. 785-807, 2015.

[3] C. Stamatis, V. Julija, M. Antonios, P. Ioulia and F. Gianluca, "Local electricity flexibility markets in Europe," Publications Office of the European Union, Luxembourg, 2022.

[4] M. R. Jokar, S. Shahmoradi, A. H. Mohammed, L. K. Foong, B. N. Le and S. Pirouzi, "Stationary and mobile storages-based renewable off-grid system planning considering storage degradation cost based on information-gap decision theory optimization," *Journal of Energy Storage,* vol. 58, 2023.

[5] X. Xu, Y. Fu and Y. Luo, "Building energy flexibility with battery energy storage system: a comprehensive review," *Discover Mechanical Engineering,* vol. 1, no. 1, 2022.

[6] Y. Hu, M. Armada and M. J. Sánchez, "Potential utilization of battery energy storage systems (BESS) in the major European electricity markets," *Applied Energy,* vol. 332, p. 119512, 2022.

[7] J. Yan, S. Liu, Y. Yan, Y. Liu, S. Han and H. Zhang, "How to choose mobile energy storage or fixed energy storage in high proportion renewable energy scenarios: Evidence in China," *Applied energy,* vol. 376, 2024.

[8] Z. Lu, X. Xu, Z. Yan, D. Han and S. Xia, "Mobile Energy-Storage Technology in Power Grid: A Review of Models and Applications," *Sustainability,* vol. 16, no. 16, 2024.

[9] C. M. Caminiti, L. G. Brigatti, M. Spiller, G. Rancilio and M. Merlo, "Unlocking Grid Flexibility: Leveraging Mobility Patterns for Electric Vehicle Integration in Ancillary Services," *World Electric Vehicle Journal,* vol. 15, no. 9, p. 413, 2024.

[10] C. Xu, P. Behrens, P. Gasper, K. Smith, M. Hu, A. Tukker and B. Steubing, "Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030," *Nature communications ,* vol. 14, 2023.

[11] T. Marentič, I. Mendek, A. Kos, M. Malenšek, H. Morais and M. Zajc, "Estimation of electric vehicles with V2G capabilities potential for market participation," in *IEEE MELECON 2024*, Porto, 2024.

[12] R. Cavalcante, A. R. d. Silva, M. Zajc, I. Mendek, L. Calearo, A. Malkova, C. Ziras, P. Pediaditis, K. Michos, J. Mateus, S. Matias, M. Brito, A. Lekidis, C. P. Guzman and A. R. N. &, “Dataset on Electric Road Mobility: Historical and Evolution Scenarios until 2050,” *Sci Data,* vol. 11, p. 1019, 2024.

[13] A. Goncearuc, C. D. Cauwer, N. Sapountzoglou, G. V. Kriekinge, D. Huber, M. Messagie and T. Coosemans, “The barriers to widespread adoption of vehicle-to-grid: A comprehensive review,” *Energy Reports,* vol. 12, pp. 27-41, 2024.

[14] T. Franzelin, S. Schwarz and S. Rinderknecht, “Smart Charging and V2G: Enhancing a Hybrid Energy Storage System with Intelligent and Bidirectional EV Charging,” *World Electric Vehicle Journal,* vol. 16, no. 3, 2025.

[15] G. Arena, A. Chub, M. Lukianov, R. Strzelecki, D. Vinnikov and G. D. Carne, “A Comprehensive Review on DC Fast Charging Stations for Electric Vehicles: Standards, Power Conversion Technologies, Architectures, Energy Management, and Cybersecurity,” *IEEE Open Journal of Power Electronics,* vol. 5, pp. 1573-1611, 2024.

[16] M. R. H. Mojumder, F. A. Antara, M. Hasanuazzaman, B. Alamri and M. Alsharef, “Electric Vehicle-to-Grid (V2G) Technologies: Impact on the Power Grid and Battery,” *Sustainability ,* vol. 14, no. 21, p. 13856, 2022.

[17] M. Ryghaug and T. Moe Skjølsvold, Pilot Society and the Energy Transition, Springer Nature, 2021.

[18] L. Ju, H. Li, J. Zhao, K. Chen, Q. Tan and Z. Tan, “Multi-objective stochastic scheduling optimization model for connecting a virtual power plant to wind-photovoltaic-electric vehicles considering uncertainties and demand response,” *Energy Conversion and Management,* vol. 128, pp. 160-177, 2016.

[19] X. Kong, J. Xiao, C. Wang, K. Cui, Q. Jin and D. Kong, “Bi-level multi-time scale scheduling method based on bidding for multi-operator virtual power plant,” *Applied Energy,* vol. 249, pp. 178-189, 2019.

[20] I. Hadjipaschalis, A. Poullikkas and V. Efthimiou, “Overview of current and future energy storage technologies for electric power applications,” *Renewable and Sustainable Energy Reviews,* vol. 13, no. 6-7, pp. 1513-1522, 2009.

[21] M. Hamwi, I. Lizarralde and J. Legardeur, “Demand response business model canvas: A tool for flexibility creation in the electricity markets,” *Journal of Cleaner Production,* vol. 282, p. 124539, 2021.

[22] G. Z. de Rubens, L. Noel, J. Kester and B. K. Sovacool, “The market case for electric mobility: Investigating electric vehicle business models for mass adoption,” *Energy,* vol. 194, p. 116841, 2020.

[23] X. Liu, X. Lin, H. Qiu, Y. Li and T. Huang, “Optimal aggregation and disaggregation for coordinated operation of virtual power plant with distribution network operator,” *Applied Energy,* vol. 376, p. 124142, 2024.

[24] M. Zajc, M. Kolenc and N. Suljanović, “Virtual power plant communication system architecture,” in *Smart Power Distribution Systems Control, Communication, and Optimization*, Academic Press, 2019, pp. 231-250.

[25] M. Kaiss, Y. Wan, D. Gebbran, C. U. Vila and T. Dragičević, "Review on Virtual Power Plants/Virtual Aggregators: Concepts, applications, prospects and operation strategies," *Renewable and Sustainable Energy Reviews,* vol. 211, p. 115242, 2025.

[26] Y. Chen, Z. Li, S. S. Yu, B. Liu and X. Chen, "A profitability optimization approach of virtual power plants comprised of residential and industrial microgrids for demand-side ancillary services," *Sustainable Energy, Grids and Networks,* vol. 38, p. 101289, 2024.

[27] Y. Chen, Y. Niu, M. Du and J. Wang, "A two-stage robust optimization model for a virtual power plant considering responsiveness-based electric vehicle aggregation," *Journal of Cleaner Production,* vol. 405, p. 136690, 2023.

[28] X. Yang and Y. Zhang, "A comprehensive review on electric vehicles integrated in virtual power plants," *Sustainable Energy Technologies and Assessments,* vol. 48, p. 101678, 2021.

[29] G. Ruan, D. Qiu, S. Sivaranjani, A. S. Awad and G. Strbac, "Data-driven energy management of virtual power plants: A review," *Advances in Applied Energy,* vol. 14, p. 100170, 2024.

[30] I. Mendek, T. Marentič, K. Anžur and M. Zajc, "A Case Study on Electric Vehicles as Nationwide Battery Storage to Meet Slovenia's Final Energy Consumption with Solar Energy," *Energies,* vol. 17, no. 11, p. 2733, 2024.

[31] C. Binding, D. Gantenbein, B. Jansen, O. Sundström, P. B. Andersen and F. Marra, "Electric vehicle fleet integration in the danish EDISON project - A virtual power plant on the island of Bornholm," in *IEEE PES General Meeting*, Minneapolis, 2010.

[32] C. Kieny, B. Berseneff, N. Hadjsaid, Y. Besanger and J. Maire, "On the concept and the interest of virtual power plant: Some results from the European project Fenix," in *IEEE Power & Energy Society General Meeting*, Calgary, 2009.

[33] S. Yang, B. Liu, X. Li, Z. Liu, Y. Liu, N. Xie and J. Ren, "Flexibility index for a distributed energy system design optimization," *Renewable Energy,* vol. 219, no. 1, 2023.

[34] A. Rashtbaryan, G. B. Gharehpetian, H. R. Baghaee and R. Ahmadianhangar, "Aggregator Index for 24-Hour Energy Flexibility Evaluation in an ADN Including PHEVs," *IEEE Access ,* vol. 12, pp. 16105 - 16116, 2024.

[35] S. Striani, T. Unterluggauer, P. B. Andersen and M. Marinelli, "Flexibility potential quantification of electric vehicle charging clusters," *Sustainable Energy, Grids and Networks,* vol. 40, p. 101547, 2024.

[36] S. R. Kirchner, "OCPP Interoperability: A Unified Future of Charging," *World Electric Vehicle Journal,* vol. 15, no. 5, 2024.

[37] N. Uribe-Pérez, A. Gonzalez-Garrido, A. Gallarreta, D. Justel, M. González-Pérez, J. González-Ramos, A. Arrizabalaga, F. J. Asensio and P. Bidaguren, "Communications and Data Science for the Success of Vehicle-to-Grid Technologies: Current State and Future Trends," *Electronics,* vol. 13, no. 10, 2024.

[38] C. Gschwendtner, S. R. Sinsel and A. Stephan, "Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges," *Renewable and Sustainable Energy Reviews,* vol. 145, p. 110977, 2021.

[39] H. Gerard, J. P. C. Avila, K. Laffont-Eloire and K. Drivakou, "Annual Report 2022: Energy Market Design and Flexibility," European Union, Luxembourg, 2023.

[40] M. Cañigueral and J. Meléndez, “Flexibility management of electric vehicles based on user profiles: The Arnhem case study,” *International Journal of Electrical Power & Energy Systems,* vol. 133, no. 107195, 2021.

[41] G. Rancilio, A. Cortazzi, G. Viganò and F. Bovera, “Assessing the Nationwide Benefits of Vehicle–Grid Integration during Distribution Network Planning and Power System Dispatching,” *World Electric Vehicle Journal,* vol. 15, no. 4, 2024.

[42] G. Gruosso, A. Mion and G. S. Gajani, “Forecasting of electrical vehicle impact on infrastructure: Markov chains model of charging stations occupation,” *eTransportation,* vol. 6, p. 100083, 2020.

[43] D. Kucevic, B. Tepe, S. Englberger, A. Parlikar, M. Mühlbauer, O. Bohlen, A. Jossen and H. Hesse, “Standard battery energy storage system profiles: Analysis of various applications for stationary energy storage systems using a holistic simulation framework,” *Journal of Energy Storage,* vol. 28, p. 101077, 2020.

[44] S. Shahriar, A. R. Al-Ali, A. H. Osman, S. Dhou and M. Nijim, “Prediction of EV Charging Behavior Using Machine Learning,” *IEEE Access,* vol. 9, pp. 111576-111586, 2021.

[45] L. Strobel and M. Pruckner, “Benchmarking Aggregation-Disaggregation Pipelines for Smart Charging of Electric Vehicles,” in *The 15th ACM International Conference on Future and Sustainable Energy Systems*, Singapore, 2024.

[46] L. Koltermann, M. C. Cortés, J. Figgener, S. Zurmühlen and D. U. Sauer, “Power curves of megawatt-scale battery storage technologies for frequency regulation and energy trading,” *Applied Energy,* vol. 347, p. 121428, 2023.

[47] F. Gerini, Y. Zuo, R. Gupta, A. Zecchino, Z. Yuan, E. Vagnoni, R. Cherkaoui and M. Poolone, “Optimal grid-forming control of battery energy storage systems providing multiple services: Modeling and experimental validation,” *Electric Power Systems Research,* vol. 212, p. 108567, 2022.

[48] E. García-Martínez, J. Muñoz-Cruzado-Alba, J. F. Sanz-Osorio and J. M. Periñán, “Design and Experimental Validation of Power Electric Vehicle Emulator for Testing Electric Vehicle Supply Equipment (EVSE) with Vehicle-to-Grid (V2G) Capability,” *Applied Sciences ,* vol. 11, no. 23, p. 11496, 2021.

[49] B. C. P. Sturmberg, J. Hapuarachchi, L. Jones, K. Lucas-Healey and J. v. Biljon, “Vehicle-to-grid response to a frequency contingency in a national grid,” *npj sustainable mobility and transport,* vol. 1, p. 7, 2024.

[50] İ. Gazioğlu, J. R. Pillai and L. A. Tuan, “Real-Life Demonstration of Flexibility Provision by Smart Charging of EVs and Stationary Battery Storage,” in *2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM)*, Hanoi, 2023.

[51] Slovenia, Statistical Office of the Republic of, “A billion data points in the SiStat Database,” [Online]. Available: https://pxweb.stat.si/SiStat/en.

[52] A. Kos, K. Koželj, D. Bobek, Ž. Stepančič and D. Gabrijelčič, “Final report of the Critical Peak Tariff project,” Flex4Grid Prosumer Flexibility Services for Smart Grid Management, 2019.

[53] Borzen, “Balancing volumes and costs,” Borzen, 2023. [Online]. Available: https://ot.borzen.si/en/Home/Market-data/Balancing-volumes-and-values. [Accessed 22 1 2025].

[54] Y. Wei, Y. Yao, K. Pang, C. Xu, X. Han, L. Lu, Y. Li, Y. Qin, Y. Zheng, H. Wang and M. Ouyang, "A Comprehensive Study of Degradation Characteristics and Mechanisms of Commercial Li(NiMnCo)O2 EV Batteries under Vehicle-To-Grid (V2G) Services," *Batteries,* vol. 8, no. 10, p. 188, 2022.

[55] O. Homaee, C. Essayeh, V. Vahidinasab, V. Tikka, G. Mendes and J. Fawcett, "Vehicle-to-Everything: Looking into the Future of Flexibility Services," *arXiv:2407.15615 preprint,* 2024.

[56] G. Franzl, S. Wilker, N. Efkarpidis and T. Sauter, "Situation Awareness by Simple Intuitive Traffic Light Signals for Smart Utilisation of Local Demand and Supply Flexibility," *Energies,* vol. 15, no. 3, 2022.