Flexibility provision of an Industrial Behind-the-Meter Energy Storage System installation through an Edge-Cloud based Energy Management System

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***Abstract*—The growing need for flexibility in Europe is driving the development of local flexibility markets (LFM). To address the uncertainties of distributed energy resources (DERs) participation in these markets, this work analyses the flexibility provision of an industrial self-consumption installation composed of photovoltaic and energy storage system resources. On the one hand, the necessary Edge-Cloud based energy management system (EMS) is presented to ensure flexibility dispatch. On the other hand, the DER flexibility provision cost impact is evaluated through a sensitivity analysis using an analytical tool and varying periodicity, flexibility request amount, activation window, and start time. The study concludes that a higher flexibility activation window implies more losses. Additionally, the flexibility requests closer to the end of the day affect the EMS baseline operation more significantly. These results are crucial for determining DER opportunity costs and setting LFM price signals, which are essential for increasing market liquidity and DER participation.**

***Index Terms*—Digital Systems, energy storage systems, energy management systems, flexibility, power system reliability.**

I. INTRODUCTION

Europe has accelerated the targets to combat climate change by increasing the objective of achieving a 69% renewable supply in all electricity generation by 2030 [1]. This will result in the necessity of constantly adjusting demand and supply in order to keep the system in balance, given the intermittent nature of these resources. According to [2], Europe's flexibility needs will be double by 2030. Flexibility is defined as the capability to modify generation or consumption patterns in response to external signals, thereby ensuring grid stability [3]. The European Commission's proposal for electricity market design [4] highlighted the flexibility potential of smaller consumers and the necessity to boost the use of demand response, energy storage and renewable energy flexibility, enhancing Member States to introduce new support schemes. Additionally, it emphasises that the short-term electricity market should ensure small-scale flexibility service providers (FSPs) active participation by lowering minimum bid sizes and it also highlights the necessity of advances in metering, information and communication technologies.

Digitalisation is presented as a flexibility enabler due to the characteristics of Internet-of-Things devices of monitoring and controlling distributed energy resources (DERs), being essential for actuating in reaction to an external signal for flexibility service provision [5], [6]. Aggregation of DERs for flexibility service provision is becoming essential as aggregators optimise their portfolio while providing economic benefits to both end-users and themselves [7], [8]. In this context, Edge-Cloud approaches are presented as indispensable, enabling capabilities of centralised, decentralised and distributed control and management [9]. Edge computing makes possible real-time data processing, automation, and analysis within coordination between different DERs. In this way, DERs gain visibility from the utility-scale view. Additionally, Cloud computing addresses the challenges of managing large data volumes by offering high computational power and extensive storage capacity [7], [9], [10] - [13].

As previously mentioned, DERs' participation in flexibility services is possible thanks to the aggregation concept and Edge-Cloud digital solutions. This led to extensive analysis of different DERs' flexibility modelling and quantification in many research works. In this regard, each work is distinguished by their peculiarities and characteristics, yet they all share that flexibility potential of DERs is quantified by incorporating a flexibility reward pricing scheme and activation periods [14] - [17]. However, within the context of a local flexibility market (LFM) framework, such incomes and eventualities remain uncertain. As a result, DERs are unlikely to engage in flexibility provision unless mechanisms are in place to ensure they do not incur financial losses.

In the provision of flexibility, DERs deviate from the primary objectives of their Energy Management System

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(EMS) strategies, thereby withdrawing from their optimal operation. This results in economic and energy losses, diminishing the local benefits they would otherwise achieve. Therefore, it is essential to quantify these losses to define the opportunity cost associated with participating in LFMs or engaging in aggregation. Within this context, several studies have been explored in the literature [18] - [21]. In this analysis, a research gap concerning the absence of a defined LFM framework and the associated uncertainties stemming from the stochastic nature of flexibility requirements was identified. Consequently, this paper focuses on a detailed evaluation of the cost implications of flexibility provision schemes in DERs.

In this context, this paper presents the analysis of flexibility provision by a real self-consumption installation containing renewable generation and a behind-the-meter (BTM) energy storage system (ESS) as DER elements. This facility is managed through an Edge-Cloud based EMS that guarantees the optimal use of resources to meet demand requirements, ensuring maximum efficiency and cost-effectiveness. To this end, a previously operational Edge-Cloud based EMS aimed at residential BTM ESS integration [22] has been scaled and replicated in an industrial use case [23] - [26]. The presented use case is located at IKERLAN's main headquarters and it includes a self-consumption installation of 100 kW photovoltaic (PV) with an average consumption power of 258 kW. It also comprises a 39kW/75kWh battery system as ESS. The objective of the integrated Edge-Cloud based EMS is to minimise generation surpluses while maximising self-consumption and performing energy arbitrage. In addition to that, the opportunity to participate in flexibility service provision has been implemented through battery capacity availability, which has been analysed using technical indicators through a sensitivity analysis within an analytical tool.

This paper is structured as follows: in Section II the flexibility provision scheme is presented. Afterwards, in Section III, the developed Edge-Cloud based EMS is described. Section IV analyses the results obtained by describing the industrial use case and the sensitivity analysis employed in the flexibility provision framework. Finally, the main conclusions are summarised in Section V.

II. FLEXIBILITY PROVISION SCHEME

LFMs have emerged as a pivotal policy priority within the European Union, driven by the European Commision's strategic initiatives to transform the energy sector [27], [28]. The European Commision's Joint Research Centre published a report on market-based instruments designed to enable Distribution System Operators (DSOs) to procure local flexibility services [29]. Additionally, [30] also provided a review of LFMs across Europe. Between the several initiatives and projects within Europe, the UK is presented as the most advanced country with operational LFMs established since 2018. In the UK, LFM, both short- and long-term, are divided by system operators and geographic zones. After analysing their operation [31], it was seen that system operators presented challenges in meeting the flexibility they had tendered. In response, Scottish Power Energy Networks (SPEN) examined the barriers to FSPs in relation to their participation in DSO LFMs [32]. The report identified significant challenges for FSPs, including revenue risks and difficulties in making long-term commitments. Consequently, in this paper, short-term LFMs were selected as the flexibility provision framework, as DERs are the targeted participants.

Figure 1. Flexibility provision scheme.

Currently, there are no operational LFMs in Spain, nor any mechanisms for flexibility procurement, which is the target country of this paper. Although OMIE (Spanish nominated electricity market operator) has under development a flexibility market platform for distribution network congestion management. This platform was presented in several projects called OneNet [33] and IREMEL [34]. Based on the LFM descriptions carried out in those two projects, the flexibility provision framework was defined. In Figure 1, the DER flexibility provision scheme for day-ahead LFM is depicted. At 14:45, the LFM is cleared for the next day's flexibility dispatch. Consequently, the aggregator receives the bid results, specifying the amount and type of flexibility accepted for a specific activation window. Following this, the aggregator will define the flexibility schedules for each DER, which then receive the corresponding flexibility requests. On the operation day, the DER will have a preparation period until the activation window; afterwards, the DER must provide committed flexibility. As it was mentioned, the uncertainty of this flexibility request is one of the main barriers for DERs. In this context, the variables that concern the local operation of the DERs are the following: a) flexibility type, b) flexibility amount, c) activation window, d) activation start, and e) flexibility request periodicity.

III. EDGE-CLOUD BASED EMS

Flexibility service provision is fully reliant on information and communication technology (ICT) infrastructure. DSOs and aggregators must ensure the correct operation of the service provision from the prequalification process until the settlement period. In this process, the aggregator also has to optimise its portfolio and provide the flexibility schedule to each DER embraced to the service. Consequently, the control and data communication between all the members must be robust.

In this context, DERs must be well-equipped to respond to all requirements and technical specifications. On the one hand, baseline operation methods have to be implemented, being this the normal operation of the DERs without any flexibility activation, in other words, the local EMS of the DER. On the other hand, communication and controllability of the DER for flexibility dispatch instructions must be ensured. In addition, real-time operations and monitoring have to be integrated. Consequently, these baselines, controls, communication, and monitoring are the foundations for evaluating service performance in the DER settlement process.

Edge-Cloud architectures present the characteristics and features previously presented. Cloud computing allows the

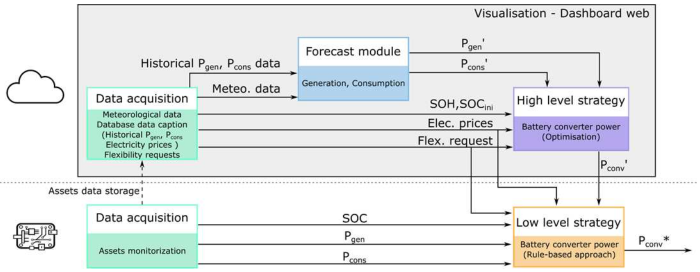

Figure 2. Edge-Cloud based EMS main diagram.

development of advanced smart energy management solutions, optimising resource allocation due to high computational and data storage capabilities. The integration of the forecasting method will facilitate the baseline calculation and improve its accuracy. By coupling Cloud resources with Edge computing, the dynamic management of DERs is obtained, integrating real-time capabilities such as direct control, communication, and asset monitorisation. Consequently, all the systems will be interconnected, and DERs visibility will be enhanced.

Given the current needs, the developed EMS in this paper was deployed within a digital environment, more concretely in an Edge-Cloud architecture, scaling and replicating the operational solution presented in [22]. Furthermore, the proper integration of flexibility dispatch instructions in the local EMS was integrated, distinguishing the DER's objectives. The main objective of the baseline operation was to maximise the self-consumption levels while providing economic savings with energy arbitrage. Besides that, when the flexibility request event came, the EMS was designed to prioritise the service provision in order to avoid the penalisation of non-fulfilment. The Edge-Cloud EMS developed comprises four modules: a) data acquisition module, b) forecast module, c) high-level strategy and d) low-level strategy. Each module is located in different environments; see Figure 2. The first three modules are deployed in the Amazon Web Services (AWS) Cloud, and later, the first one with the last one are implemented in the Edge device. The modules deployed in the Cloud are executed once a day, while the ones located in the Edge are executed in real-time during the operation day.

A. *Data acquisition module*

The data acquisition module is responsible for collecting all the necessary data for the proper operation of the EMS. The data acquisition model deployed in the Edge carries out the monitoring of all installation assets and provides this data to the Cloud for storage in the database. Regarding the Cloud, the module performs meteorological data requests to the Basque Meteorological Agency database [35]. Additionally, historical data on generation and consumption, as well as electricity prices, are collected from the Cloud database. Lastly, the data acquisition module will receive the flexibility request sent by the aggregator.

B. *Forecast module*

Based on historical and meteorological data, the forecast module predicts PV generation and industrial building consumption. These predictions are generated as hourly profiles for the operation day. The machine learning technique used for the forecasts was the random forest algorithm.

C. *High-level strategy*

The high-level strategy is a dynamic programming optimisation algorithm which schedules the battery operation. The main objective of the strategy is to reduce the electricity bill while maximising the self-consumption levels of the installation.

D. *Low-level strategy*

The low-level strategy is a rule-based approach designed to maximise the self-consumption of the installation by minimising surplus energy injected into the grid. Additionally, to enhance benefits, the battery is also utilised for energy arbitrage. This strategy has been deployed on the Edge device due to the need for real-time measurements of generation, consumption, and battery state of charge to manage and adjust the battery effectively.

Once explained the local operation of the EMS, an extra objective was introduced into the strategy, as previously mentioned. This is related to the EMS modification for flexibility service provision and will only be activated when a flexibility request is received from the aggregator. When this event occurs, the main objective of the low-level strategy is replaced by the minimisation of the risk of flexibility dispatch non-compliance due to a shortage of reserves. The ESS will be scheduled to ensure the service by reserving the necessary capacity of the request plus a 5% additional margin to confront uncertainties. In this preparation time, the energy arbitrage will be allowed with the remaining available capacity.

IV. RESULTS

This study aims to evaluate the opportunity cost of flexibility provision for DERs within the presented framework in Section II. Once presented in Section III, the DERs necessary developments and deployments for flexibility service participation and provision, in this section, flexibility provision impact analysis is conducted, more concretely, for a specific case study (described hereinafter) within the low-level EMS strategy mentioned above. Finally, the results obtained in the sensitivity analysis are discussed.

A. *Case Study*

The case study intends to ground concepts into a specific industrial use case, more concretely, IKERLAN's main headquarters living laboratory (Figure 3). This industrial case study is composed of a self-consumption installation of 100

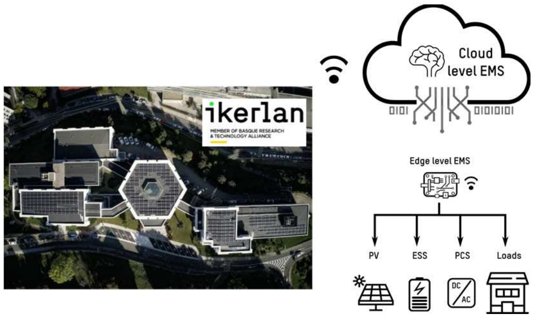

Figure 3. Industrial case study.

kW PV and an average power consumption of 258 kW with a 6.2TD contracted electricity tariff (Spanish company and large industrial tariff in 2023, BOE-A-2022-23737 and BOE-A-2022-21799). A battery ESS of 39kW/75kWh has been integrated in the installation with the presented Edge-Cloud based EMS in order to maximise self-consumption while performing energy arbitrage and allowing flexibility service provision.

B. Sensitivity analysis

This paper proposes a set of flexibility sensitivity analyses based on LFM participation parameters that generate uncertainty to DERs. The study was conducted for the industrial case study presented, covering a one-year period, specifically considering the year 2023. To be able to evaluate the impact of different flexibility provision scenarios, only the low-level strategy of the EMS was executed in the analytical tool.

The parameters selected for the sensitivity analysis were deducted from the flexibility provision scheme presented in Section II. Firstly, it was assumed that the direction of the flexibility requirements would be downwards, as the use case involves an industrial company with high consumption levels with respect to generation, meaning that consumption will be reduced for a specific time period. The defined parameters are presented in Table 1. As mentioned in Section III, flexibility will be provided by reserving ESS capacity. Consequently, different levels of flexibility requirements were selected concerning the 39 kW of ESS power. Additionally, the maximum duration of the service window was determined by the ESS energy capacity (75 kWh) and the flexibility requirement; therefore, different durations were defined for each requirement scenario. In order to evaluate the impact of the activation in different periods of the day, six different dispatch start times were defined. Finally, three types of periodicities were selected: a) daily, b) weekly or c) monthly activations. As a result, 189 different combinations were defined and simulated.

TABLE 1. SENSITIVITY ANALYSIS CHARACTERISTICS

Flexibility requirement (kW)	30		20			10						
Service window (h)	1	2	1	2	3	1	2	3	4	5	6	7
Activation start time	04:00		08:00		12:00		16:00		20:00		22:00	
Periodicity	1				7				31			

Figure 4 illustrates a comparison of the main operation on the 6th of March (labelled as a and representing a low self-consumption level day) and the 14th of July (labelled as b and representing a high self-consumption level day) for a daily activation at 08:00, with an activation window of 2 hours and a flexibility requirement of 30 kW. In the first chart, labelled power, the following elements are depicted: the power generated by the PV installation (blue), the consumption power (red), the ESS power without flexibility requirements in the EMS (purple), and the ESS power with flexibility requirements in the EMS (orange). In the second chart, labelled as State-of-Charge (SOC), the SOC profiles corresponding to different EMS operations are shown: in purple (without flexibility requirements) and orange (with flexibility requirements). Bellow this graph, electricity prices are plotted. Finally, the last chart displays the flexibility activation window.

As it can be seen, the battery is fully charged at the beginning of the day on both operation days, coinciding with the operation with the lowest electricity prices in both EMS configurations. In the case of no flexibility activation, the ESS is discharged during the high electricity prices at 09:00. In contrast, with flexibility activation at 08:00, the discharge began at 08:00, preventing the ESS from supplying power for consumption at high prices, resulting in a non-optimal operation of the DERs. After this point, both EMS configurations operate identically for their respective day, as no further flexibility is required. In terms of full equivalent cycles (FECs), there is no alteration, as the battery charges and discharges the same amount of energy in both scenarios.

After conducting the sensitivity analysis, several general findings were obtained. As expected, higher losses respect to the benefits of the local EMS were observed with daily activation (Figure 5 graph a). The weekly and monthly operation is in other orders of magnitude, resulting in closer to the local EMS performance. Moreover, these losses were directly influenced by the power and energy involved in the activation, with the most adverse cases linked to energy. This indicates that the larger the activation window, the greater the negative impact on the operation of the local EMS, as it can be seen in Figure 5 (graph c). In addition to that, having an activation window closer to the end of the day resulted in increased losses (Figure 5 graph b), a direct consequence of the preparation period. After these general results, each case study was divided into power requirements and investigated in more detail.

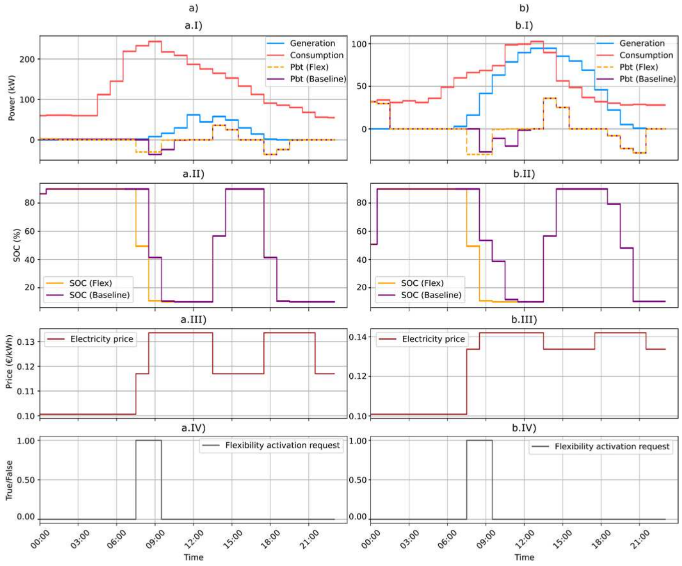

Figure 4. EMS operation for a) high energy consumption and low generation day and b) low energy consumption and high generation day with and without flexibility provision, I) power profiles, II) SOC, III) electricity price and IV) activation request.

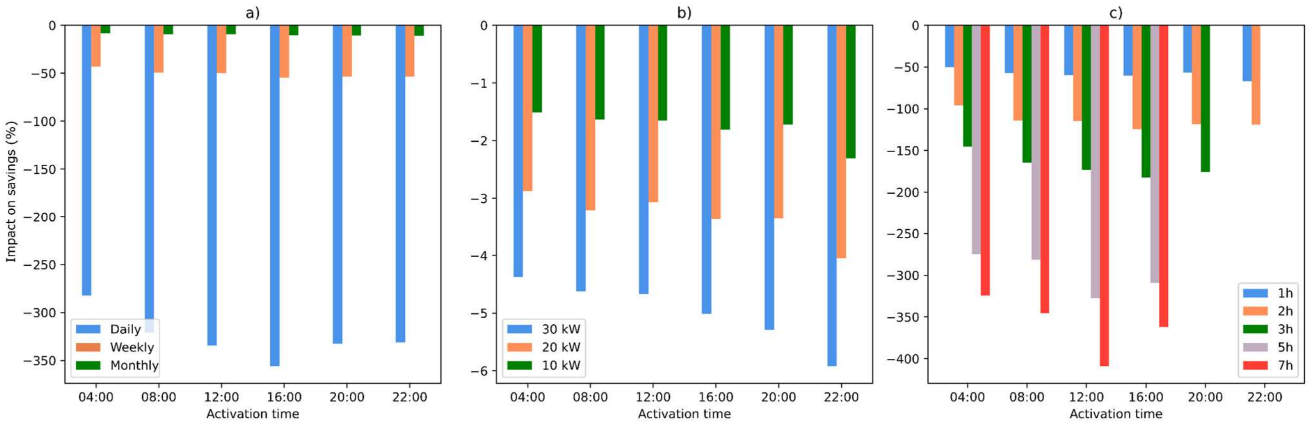

Figure 5. Sensitivity analysis main results: a) daily, weekly and monthly operation impact (30 kW requirement, 2 hour case), b) power requirement impact (30 kW, 20 kW and 10 kW) within a monthly 1 hour activation window and c) activation window impact (from 1 hour till 7 hours) within a daily 10 kW requirement.

In the case of 30 kW flexibility activation, the higher losses (-356%) were obtained within an activation window of 2 hours at 16:00 and a daily operation (Figure 5 graph a). With this flexibility requirement, at 18:00 (the highest electricity price period), the ESS cannot meet the consumption requirements because of its full discharge. In contrast, the scenario of a monthly activation of a 1-hour activation window at 04:00 obtained the closest results to the benefits of the local operation (-4.37%), see Figure 5 graph b. On the other hand, analysing the number of FECs, a maximum increment of 74% was obtained with a daily operation of 2 h at 04:00. This is a consequence of the price signals at the beginning of the day, as it was seen in Figure 4.

On the other hand, in the case of 20 kW of flexibility activation, 360.27% of higher losses were obtained within a daily operation and an activation window of 3 hours at 16:00, as in the previous case. Meanwhile, the lowest increment on the losses was obtained again at 04:00 and 1-hour service window within a monthly operation (-2.87%), as it can be seen in Figure 5 graph b. Regarding the FEC amount, a maximum increment of 73.17% was obtained at 04:00 with a daily service window of 3 hours. This resulted in a similar tendency of the previous case.

Finally, in the lower flexibility requirement analysed, 10 kW, a maximum value of -409.11% of losses was obtained with a daily operation at 12:00h and an activation window of 7 hours (Figure 5 graph c). Regarding the lowest benefit losses of -1.51%, they were obtained at 04:00 within an activation window of 1 hour and a monthly requirement (Figure 5 graph b). Lastly, maximum FECs were obtained at 04:00 at a 3-hour daily activation window, a 37.30% increment.

V. CONCLUSIONS

This paper has analysed the flexibility provision by a real industrial self-consumption installation composed of renewable generation and a BTM ESS. On the one hand, the current flexibility service provision scenario was reviewed, and the selected scheme was presented. On the other hand, considering the clear need for ICT infrastructure for the DERs' participation in flexibility service provision, the description and development of an Edge-Cloud based EMS was presented.

In order to evaluate the main factors that generate uncertainty in DERs' participation in flexibility service provision, a sensitivity analysis was carried out for the presented industrial use case of a self-consumption installation of 100 kW PV with an average consumption power of 258 kW and a 39kW/75kWh ESS. The study was carried out by varying the flexibility power requirement, service window duration, service window start time and requirement periodicity. As it was expected, the higher the amount of energy discharged outside the local EMS operation (baseline), the higher the impact is. It was concluded that although power and energy requirements are related; while speaking of the same energy provision level, a longer activation window has a greater impact than a shorter duration with higher power. Regarding the activation time, it was seen that the earlier the activation period, the lower the impact is and vice versa. Furthermore, in terms of periodicity, as expected, the higher amount of activation implies more losses. Weekly and daily activations are thus approximated.

This work presents the importance of assessing the impact of flexibility provision in DERs through an analytical tool. The results are crucial for both DER operators to determine their opportunity costs and for DSOs or market operators to design appropriate LFM price signals. These price signals play a key role in ensuring DER participation, which is essential for maintaining market liquidity. Thus, this tool provides valuable insights into the order of magnitude of the incentives required to encourage DER participation.

The study carried out in this paper allows to ground concepts within a real case study, being a further step towards the future decentralised and digitalised electricity system with new electricity markets such as LFM, enhancing the power system reliability and resilience.

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