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# Economic Opportunities of Power Curtailment and Peak Shaving on Residential PV-BESS Systems


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***Abstract*—In low-voltage distribution networks, the high penetration of renewable energy generators in residential buildings has proven challenging for system operators. In response, the grid operators can reinforce the grid infrastructure or deploy battery energy storage systems throughout the network to compensate for the voltage fluctuations. Alternatively, new energy markets for ancillary services have been proposed to involve the prosumers; however, most are at medium and high voltage levels. This paper investigates, from a cost perspective, what conditions can make it attractive for individual prosumers to participate in a low-voltage ancillary service market, specifically power curtailment and peak shaving. We considered a prosumer with a 2 kWp PV system for both ancillary services, adding a 10 kWh battery for the peak shaving case. Curtailing power to comply with the maximum power exchange with the grid does not create any significant change in the LCoE of the PV system, keeping it near 0.072 €/kWh for permitted return grid powers above 1.25 kW. Scenarios closer to zero-injection increase exponentially the LCoE to 0.222 €/kWh. Using a semi-empirical ageing model, we estimated the degradation of the batteries for the cases with and without providing peak shaving, concluding that doing peak-shaving to avoid demanding more than 1 kW from the grid extends the battery life by up to 320 % while increasing its LCoS only 9.5 % when compared to a zero-consumption scenario due to the reduced depth-of-discharge and number of cycles. The results suggest that power curtailment and peak shaving can be attractive for prosumers, thus creating opportunities for ancillary services business models at the residential scale.**

***Index Terms*—Ancillary services, Battery Degradation, Residential Energy Market, Peak Shaving, Power Curtailment**


## I. Introduction

Energy transition encourages deploying distributed renewable energy sources throughout the energy supply chain to tackle the dependence on fossil fuels for energy generation. At the low-voltage distribution networks, high penetration of renewable energy generators, mostly photovoltaic systems, has proven challenging for system operators both at the technical [1] and market level [2]. The stochastic mismatch between generation and consumption causes bidirectional flows in the network that, when aggregated in multiple nodes, cause overvoltages and grid congestion. This phenomenon is leading distribution system operators (DSOs) to enforce curtailment, like in the UK [3] and Germany [4]. In the Netherlands, curtailment is essential to shape the electric network as efficiently as possible [5]. However, DSOs require a legal framework to enforce curtailment. The review in [1] demonstrated that grid operators normally reinforce the grid infrastructure (feeders and substations) to overcome the challenges created by distributed energy resources (DERs), which is costly and time-consuming [3]. Alternatively, they can install and manage battery energy storage systems (BESS) throughout the network to compensate for the voltage fluctuations, either by charging during high voltage periods or discharging during low voltage periods. This approach requires complex studies to determine the optimal location and size of the storage system. [6]. New energy markets for ancillary services have been proposed to involve the prosumers with storage devices; however, most are at medium and high voltage levels [7], [8].

Energy storage plays a major role in providing flexibility to the distribution networks. The review in [9] evaluated different energy storage systems based on their suitability to provide one or more ancillary services to support grids with high RES penetration. From an energy perspective, BESSs were chosen as the most versatile technology thanks to its fast response, energy and power densities, and decreasing prices. However, it was also recommended that the degradation changes be studied when providing ancillary services, as they might affect their profitability. Similar to generation technologies, the profitability of energy storage systems can also be evaluated using a levelized cost. The levelized cost of storage (LCoS) is the ratio of cost vs. energy supplied; therefore, for a business opportunity using a BESS to be attractive, the earnings should be above the LCoS. In [10], the reduction of income due to


The project was carried out with a Top Sector Energy subsidy from the Ministry of Economic Affairs and Climate, carried out by the Netherlands Enterprise Agency (RVO). The specific subsidy for this project concerns the MOOI subsidy round 2020.

degradation for different applications was studied. A detailed review of the costs related to PV and BESS is provided in [11] and used to calculate the LCoS for different yearly cycling conditions. The economic opportunities for second-life electric vehicles BESS in the day-ahead dispatch market in California were studied in [12], concluding that frequent cycling patterns to provide ancillary services accelerate the BESS degradation.

Battery degradation can be split into calendar and cyclic ageing modes. Calendar ageing is always present and is mainly driven by the formation of the solid electrolyte interphase (SEI) layer due to unwanted side reactions [13]. Calendar ageing can be accelerated by keeping the BESS idle with high SoC values and high ambient temperature [13]–[15]. Cyclic ageing is caused by increased SEI formation due to particle cracking [16] as well as lithium plating [17]. There are three common categories of battery degradation models. Physics-based models mathematically describe the electrochemical mechanisms [18], requiring high computational power. Empirical models fit functions using large experimental datasets (e.g., using equivalent circuits or machine learning methods) [19]. In between, semi-empirical models fit a known equation over measured degradation data to obtain a model [20]. In this work, we will focus on the latter. In [21], the authors derive a semi-empirical model for LFP/Gr cells, using the Arrhenius equation to model cyclic ageing and considering temperature, C-rate, and energy throughput. Calendar ageing is not included, and the influence of DoD is neglected because LFP has a low dependency on DoD [22]. In [23], the authors derive a similar model for NMC-LMO/Gr cells, including calendar and cyclic ageing. In this model, temperature, SoC, DoD, C-rate, and energy throughput are included, but the influence of SoC on cyclic ageing is overlooked (in this work, we used this model). In [15], the influence of middle SoC was added to the cyclic model, but the influence of temperature was omitted.

This work evaluates the impact of supporting the grid by power curtailment and peak-shaving on the levelized cost of energy and storage for individual prosumers in a residential case scenario in the Netherlands. Namely, the contributions are

- the quantification of the PV energy lost due to power curtailment and its effect on the LCoE,
- the quantification of the BESS degradation due to peak-shaving and its effect on the expected end-of-life and LCoS, and
- the proposal of limits for power curtailment and peak-shaving that minimize the impact in the levelized costs.

Our results provide insight into implementing ancillary services in low-voltage distribution networks for other case scenarios.

## II. Mathematical Descriptions

### A. Power Demand Model

To simulate the demand behaviour of a house, we created a synthetic load profile based on a probability function for activating different appliances throughout the day. This way, the power demand is given as

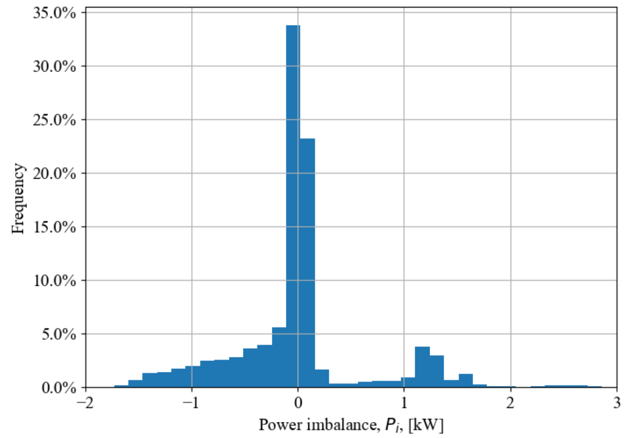


Fig. 1: Power imbalance between the load and the PV generation without curtailment.

$$P_L(k) = \sum_{i=1}^{n} P_i(k)\, \mathbb{P}_i\left(\{\omega_i(k) \in \Omega_i(k)\}\right), \tag{1}$$

where $\mathrm{P}_i$ is the power per appliance $i$, $\mathbb{P}_i$ is the activation probability at time $k$, and $\Omega_i(t)$ is the event space at the instant $k$ [24]. We considered typical power consumptions based on typical load profiles of the appliances with higher demand [25] and created a yearly load profile.

We used irradiance data from the Royal Netherlands Meteorological Institute (KNMI) to create a power profile for the PV generation of a 2 kWp system in Delft, The Netherlands. This way, we determined the power exchanged with the grid (imbalance) by combining the PV generation and load profiles. In Fig 1, we presented a histogram of the power imbalance, which better represents the frequency at which different powers are demanded or returned to the grid.

### B. Battery Degradation Model

The literature presents several methods to estimate BESS degradation depending on the available data. Battery ageing depends on numerous parameters, such as operation temperature $T$, C-rate, state of charge SoC, and cathode chemistry. In this paper, a control-oriented semi-empirical model is used [23], [26]. The model aggregates the degradation mechanisms (e.g., SEI layer growth, particle cracking, and active material loss) into the calendar ageing

$$i_{\text{cal}} = c_5 . e^{-\frac{24\,\text{kJ}}{RT}} . \sqrt{t}\,, \tag{2}$$

and cyclic ageing

$$i_{\text{cycle}} = \frac{c_1 . c_3}{c_4} . e^{c_2 . |i|} . (1 - SoC) . |i|\,, \tag{3}$$

resulting in the total current loss

$$i_{\text{loss}} = i_{\text{cycle}} + i_{\text{cal}}\,, \tag{4}$$

TABLE I: Parameters for the empirical degradation model [23]

| Parameter | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ |
|---|---|---|---|---|---|
| **Value** | 0.0008 | 0.39 | 1.035 | 50 | $1.721 \times 10^{-4}$ |

with the charge $Q$ behaviour being

$$Q_{t+1} = Q_t - \frac{\Delta t}{3600}.i_{\text{loss}}\,, \tag{5}$$

where $c_i$ are empirical parameters coming from curve fitting (see Table I), $R$ is the gas constant and $T$ is the temperature.

### C. Energy Management System

Two ancillary services are considered for this work: power curtailment and peak shaving. The former comprises a stand-alone PV system, whereas the latter couples a PV system with a BESS. For each case, we considered a threshold limit as the control signal. Considering the power purchased from the grid as positive and the returned power to the grid as negative, the threshold for the peak-shaving defines the maximum amount of power the prosumer can purchase from the grid ($P_{\text{grid}}^{\text{max}}$). Similarly, the power curtailment threshold defines the maximum power the prosumer can inject into the grid. To maintain the sign convention, an injection is considered a negative purchase; thus, the curtailment threshold ($P_{\text{grid}}^{\text{min}}$) sets the minimum power the prosumer can purchase from the grid. In both cases, we assumed the thresholds are set by the DSO and, if not followed, the prosumers could be penalised. In this work, we did not include penalty costs. Note that, in the case of power curtailment, it is possible to follow the control order at any time, whereas that is not necessarily the case for peak shaving. The reason is because of the BESS's capacity, SOC, and power limitations; there might be cases where the BESS has to absorb power, but it cannot do so because its SOC is too high, or vice versa. In such cases, the energy management system (EMS) will compensate with power from the grid, following the EMS proposed in [27].

## III. Results and Discussion

### A. Power Curtailment

We evaluated the curtailment algorithm for thresholds between 2 and 0 kW based on the power imbalance presented in Fig. 1. Fig. 2 shows the accumulated energy of the system by the source during 25 years, considering a linear degradation in the PV modules. As expected, due to the lower frequency in higher power injections, the curtailed energy decreases notably after a threshold of around 1 kW. At this point, the revenue loss due to the curtailed generation increases the system's levelized energy cost, as shown in Fig. 3, making the investment less profitable for the prosumer. Note that before 1 kW, the revenue loss due to the curtailed energy did not have a significant impact on the overall LCoE. Considering an investment of €4000 and no operational costs for the PV system, the LCOE of the system increases exponentially from 0.0722 €/kWh when no curtailment is applied to 0.222 €/kWh when the EMS does not inject any power into the grid, considering a discount rate of 8 % and an inflation rate of 2 %. Given the

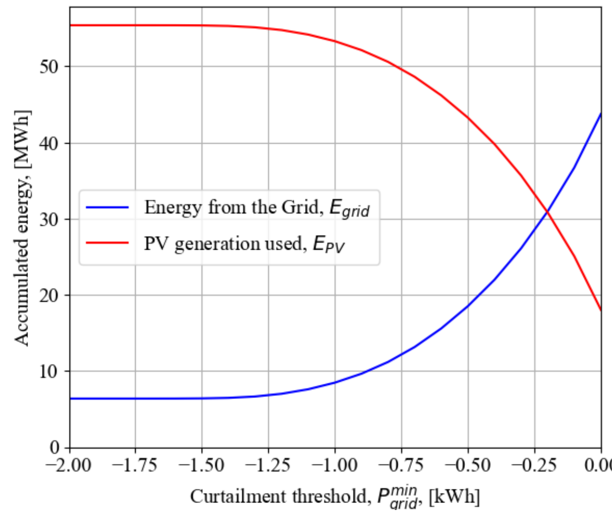


Fig. 2: Accumulated energy from the PV and the grid based on the curtailment threshold.

above, PV system owners could support the network operators by curtailing the power to some degree without affecting considerably their return on investment.

For this case scenario, we assumed a PV system sized to achieve a net-zero energy building; however, our results provide insight into how other case scenarios would behave. On the one hand, residential PV systems with yearly accumulated generation below the accumulated energy consumption still would likely inject power into the grid due to the irregular residential power profile and its mismatch with the PV power generation. On the other hand, oversized PV systems aimed to profit out of the feed-in tariff would be especially less profitable under power curtailment conditions, although one could argue that residential PV systems should not be oversized, as they are designed for self-consumption. The curtailment threshold where the LCoE starts increasing would also change based on the ratio of accumulated PV generation vs. accumulated energy consumption, as well as on the load pattern. Nevertheless, the general exponential behaviour is expected to remain in residential case scenarios.

### B. Peak-Shaving

We performed a similar analysis with peak-shaving, considering a 10 kWh/2.56 kW BESS. In this case, the EMS will dispatch energy from the BESS when the power demanded from the grid is above the peak-shaving threshold. Fig. 6 shows the amount of energy stored in the BESS before its SOH (set at 80 %), suggesting that lower thresholds reduce the amount of energy stored during the life of the BESS. This can be explained by comparing the distribution of BESS power at a particular SoC. In Fig. 4, we provide the distribution of the starting SoC of the BESS for every dispatch point. As can be seen, the power range the BESS dispatches is reduced by increasing the peak-shaving threshold, keeping the SoC of the

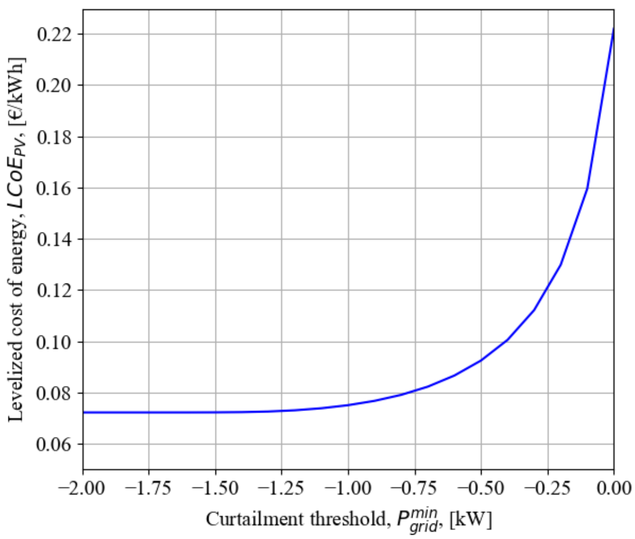


Fig. 3: LCoE of the PV system based on the curtailment threshold.

BESS close to its maximum allowed (90 % in this case). The correlation with Fig. 1 is clear, as the discharge points (positive BESS power) seem to centre near 0, 1.5 and 2.5 kW in the power imbalance. As the peak-shaving threshold increases, the points near 0 kW in the power imbalance stop showing, and the points near 1.5 kW and 2.5 kW in the power imbalance displace towards BESS powers closer to 0 kW. For example, in Fig. 4a, there are two clear clusters of BESS power, 0 kW and 1.5 kW, coincident with Fig. 1, as the peak-shaving threshold is 0. In Fig. 4b, there is still, albeit minor, a cluster in 0 kW, but the cluster that was near 1.5 kW in Fig. 4a is now near 1 kW, as the peak-shaving threshold is now 0.5 kW; thus, the relative power between the threshold and the imbalance cluster is now 1 kW instead of 1.5 kW. The cluster near 2.5 kW in the power imbalance became more visible in higher peak-shaving thresholds because the frequency of these powers is around two orders of magnitude lower than the peak centred at 0 kW and one order of magnitude lower than the peak centred at 1.5 kW. Therefore, when the peak-shaving threshold increases, the BESS no longer covers lower power imbalance points, thus increasing the relative frequency of the higher imbalance powers. Also, the BESS might not have enough energy always to comply with low peak-shaving thresholds, as shown in Fig. 5.

Fig. 6 shows a decrease in energy accumulated in the BESS before its EoL. This behaviour is because the frequency of powers above the threshold decreases the higher the threshold (see Fig. 1), which, added to a smaller difference between the power imbalance peaks and the threshold, keeps the BESS in higher SoCs, as shown in Fig. 4. This way, the main degradation mechanism of the BESS is due to calendar ageing instead of cycling, thus degrading the BESS without using it.

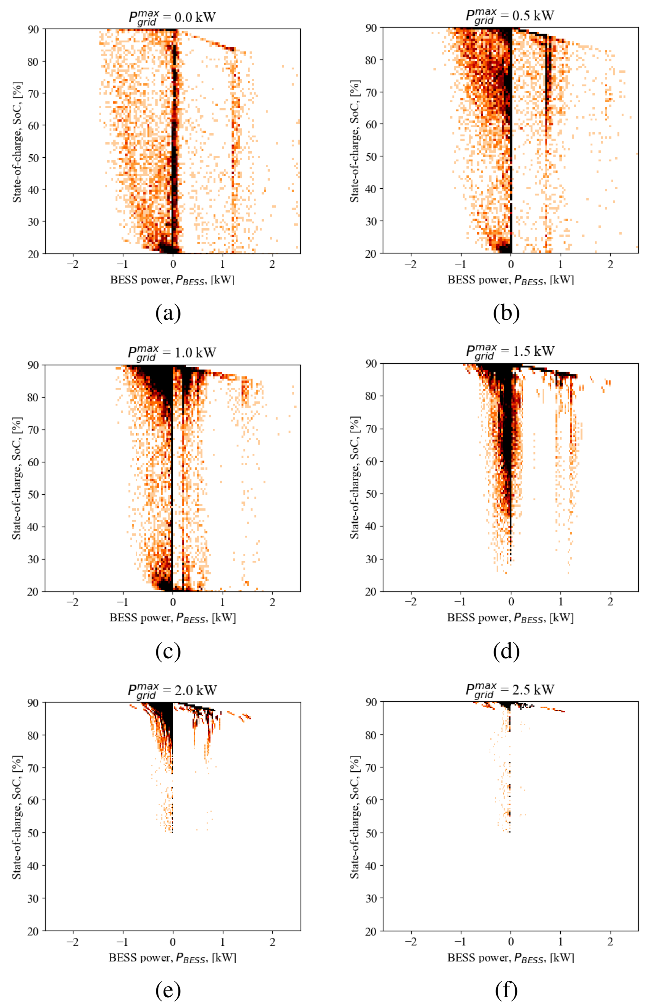


Fig. 4: Distribution of the starting SoC and power for the BESS for different peak-shaving thresholds.

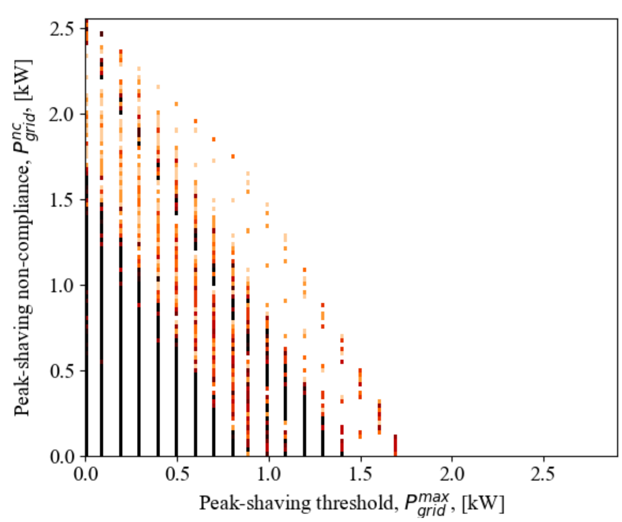


Fig. 5: Power demanded from the grid above the peak-shaving threshold.

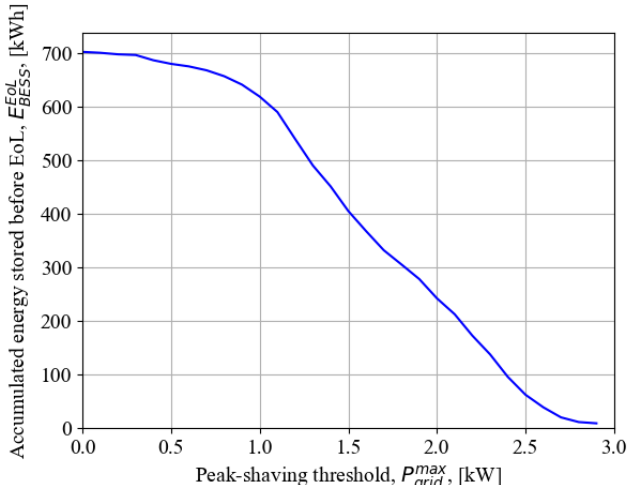


Fig. 6: Accumulated energy in the BESS before EoL.

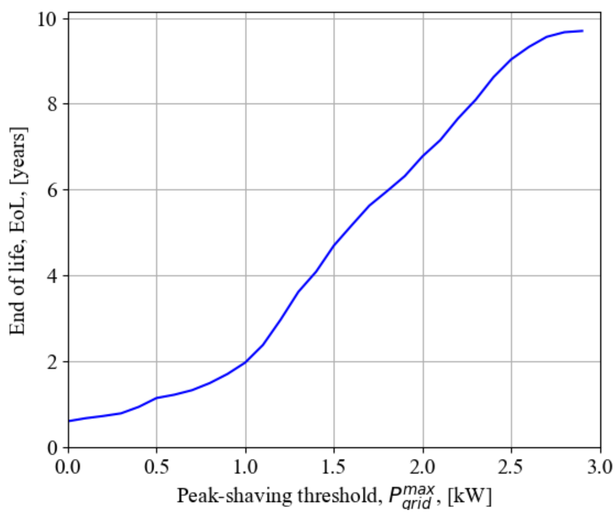


Fig. 7: BESS expected end of life as a function of the peak shaving threshold.

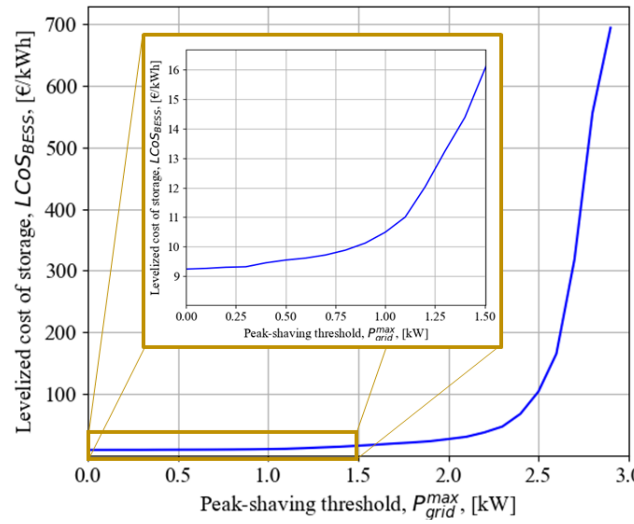


Fig. 8: LCoS as a function of the peak shaving threshold.

In lower thresholds, the BESS has to deliver more power; thus, the DOD is higher, and the BESS degrades faster, reducing its lifetime as shown in Fig. 7. This is reflected in the levelized cost of storage presented in Fig. 8. Considering an investment of €6 500, the LCoS increases exponentially, from 9.25 €/kWh to 693.65 €/kWh. The zoom in the figure provides the LCoS for peak-shaving thresholds below 1.5 kW. The LCoS slowly increases from 9.25 €/kWh at the zero-consumption scenario to 10.12 €/kWh at a threshold of 1 kW, increasing exponentially afterwards. In this case, as most of the power consumption is below 1 kW, setting the threshold above this number would result in an underused battery, increasing the levelized cost of storage as less energy is provided by the battery.

Fig. 4 also provides insight into the role of the BESS sizing, both in capacity and power, with respect the the peak-shaving threshold. In this case, the 10 kWh/2.56 kW seems undersized for peak-shaving thresholds near 0 kW, where the extensive usage of the BESS, both in number of cycles and DoD, would accelerate its ageing, suggesting that higher capacity would allow a less deep cycling. Similarly, the inverter capacity seems insufficient to cover the highest, albeit less frequent, peaks. The opposite effect is shown in more permissive thresholds, where the BESS seem oversized. Other case scenarios would probably show different results regarding the expected end-of-life of the battery and its LCoS; but similar to the analysis on the power curtailment case, the behaviour is expected to be similar. This would allow designers to determine the inflexion points for different cases and propose thresholds based on the characteristics of the prosumer's load profile.

## IV. Conclusions

This paper investigated, from a cost perspective, what conditions can make it attractive for individual prosumers to participate in a low-voltage ancillary service market, specifically power curtailment and peak shaving. For power curtailment, we considered a prosumer with a 2 kWp PV system and a maximum return power of 1.8 kW. Power curtailment ensured a predefined power exchange with the grid limit ranging from 0 to 2 kW. There was no significant change in the LCoE of the system for limits above 1.25 kW; however, limits below 1.25 kW towards a zero-injection scenario increased the LCoE exponentially from 0.0722 €/kWh to 0.222 €/kWh.

We coupled a 2 kWp PV system with a 2.56 kW/10 kWh BESS to evaluate peak-shaving to the same load profile. Using a semi-empirical ageing model, we estimated the degradation of the batteries for the cases with and without providing ancillary services, allowing us to estimate the LCoS. The LCoS tend to increase when increasing the peak-shaving threshold, having a minimum value of 9.25 €/kWh. The LCoS remains somewhat constant until a threshold of 1 kW (with an LCoS of 10.12 €/kWh). After that point, the LCoS increases exponentially because the imbalance power has low frequencies in that region, leading to lower energy stored in the BESS and higher calendar degradation. Lower permitted power exchange limits, near zero-consumption, require more frequent battery usage, resulting in less stored energy and faster degradation. Also, scenarios with permitted power exchanges below 1.5 kW often fail to meet the limit for the studied system, urging higher PV and BESS capacities, ultimately leading to an oversized system. Our results provide insight into the behaviour of the LCoE and LCoS for other case scenarios as, even though different prosumers would have different loads or generation conditions, both levelized costs are expected to increase exponentially after a certain threshold.

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