Analysis of battery energy storage systems participation in multi-services electricity markets

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***Abstract*— This work performs a comparative analysis of battery energy storage system (BESS) participation in the multi-services electricity market, considering the optimal operating cost and better profitability for the BESS portfolios. A comparison of the application of these portfolios in different market conditions is proposed: (i) energy-only market, (ii) reserve-only market, (iii) sequential energy and reserve market, and (vi) joint energy and reserve market. For each BESS portfolio, hourly strategies for buying and selling offers are proposed, to maximize the revenue, accounting for the expected load and generation variations in the grid. The analysis of the BESS strategies is carried out through a case study based on actual generation data, where operating costs and BESS flexibility are assessed. One conclusion is that, even though, BESS makes a profit by participating in single markets, the best strategy is to participate in both energy and reserve markets, especially in the presence of a joint energy and reserve market model.**

***Index Terms*-- Battery Energy Storage System, Distributed Energy Resources, Electricity Markets, Reserve Market.**

I. Introduction

In recent years, a massive amount of distributed energy resources (DER) has been deployed close to the load centres, mainly renewable energy sources (RES) in the distribution grid, motivated by economic, environmental, security, and reliability aspects. Though RES presents generation variability and intermittency, this can be seen as an opportunity to improve the BESS participation at the distribution grids [1], [2]. On the other hand, the high investments in BESS are not compensated by the current market models [3], so it is urgent to study its multiservice operation to maximize its profitability. Several works approach the optimization of the BESS operation, however, an analysis of multiservice BESS operation is necessary [4]–[6], such as its simultaneous participation in energy and reserve markets. Different works studied the sequential [7] and joint [8] energy and reserve markets considering RES, but disregarding the participation of BESS. The authors in [9] and [10] integrated BESS operation in the joint energy and reserve market, but the analysis focuses on the battery's degradation and its life cycle, lacking an assessment of the impact of different market operating strategies. This gap is filled by [9] and [11], which analyze BESS's integration in the energy and reserve market models following the American (joint) and European (sequential) models, respectively. However, a full comparison between these two market models (similar to [12]) and the energy-only and reserve-only markets is lacking. A comparative analysis of the economic and systemic benefits is also required, justified by the future perspectives of changes in market models [13] and concepts of service flexibility [14], [15].

In this way, this work proposes to analyse the participation of BESS in the energy and reserve market, accounting for the different market mechanisms. More precisely, it aims to assess the economical profitability of BESS participating in the energy and reserve markets. Within this, four different market participation strategies are identified, following the participation in the energy-only, reserve-only, sequential and joint market models.

The paper is organized as follows: Section II presents the proposed methodology and mathematical formulation for each market scheme, namely energy-only, reserve-only, sequential and joint market models. Section III presents the case study for BESS participation in energy and reserve markets, considering a 37-bus IEEE distribution grid. Section IV gathers the main conclusions of this work.

II. BESS Participation in Energy Markets Accounting for Grid Constraints

The proposed model for BESS participation in energy and reserve markets considering their impact on the distribution grid is split into two phases. In the first stage, a list of options for BESS portfolios considering the placing and sizing in the distribution grid is proposed. Subsequently, a comparison of the application of these portfolios under different market models is performed, namely: (i) the energy-only market; (ii) the reserve-only market; (iii) the sequential energy and reserve market, which is based on a sequential running process of the energy-only market and then followed by the reserve-only market; and (iv) the joint energy and reserve market models are assessed.

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A. Energy-only market

The energy-only market model performs the energy dispatch of all resources for energy, accounting for their economic and technical impact on the grid. The aim is to minimize the system operating costs, accounting for the costs related to all energy resources, including energy export and load shedding, given by

$$Min\ f = \sum_{t=1}^{T} \Big[\sum_{g=1}^{N_{DG}} \big(P_{DG\ (g,t)}\ \pi_{DG\ (g,t)} + P_{DG(g,t)}^{Cut}\ \pi_{DG\ (g,t)}^{Cut} \big) - P_{Grid\ (t)}^{Export}\ \pi_{Grid\ (t)}^{Export} + \sum_{l=1}^{N_{load}} \big(P_{L(l,t)}^{Shed}\ \pi_{L\ (l,t)}^{Shed} \big) + \sum_{st=1}^{N_{Storage}} P_{Dch\ (st,t)}\ \pi_{Dch\ (st,t)} - P_{Ch\ (st,t)}\ \pi_{Ch\ (st,t)} \Big] \tag{1.1}$$

where $P_{DG\ (g,t)}$ is the power of generator (g) for each delivery time (t) and $\pi_{DG\ (g,t)}$ represents the cost associated. $P_{DG(g,t)}^{Cut}$ is the power cut in renewable generators and $\pi_{DG\ (g,t)}^{Cut}$ represents the costs of these cuts. ($P_{L\ (l,t)}^{Shed}$) corresponds to the amount of energy that each consumer (*l*) ceased to receive, and the respective cost of that interruption is $\pi_{L\ (l,t)}^{Shed}$. $P_{Dch\ (st,t)}$, $P_{Ch\ (st,t)}$, $\pi_{Dch\ (st,t)}$ and $\pi_{Ch\ (st,t)}$ represent the discharging and charging power and costs in time (*t*), respectively. The BESS operation is constrained by equations (1.2) to (1.6), which includes the charging (1.2) and discharging (1.3) limits, the non-simultaneity of charging/discharging (1.4), the BESS limits (1.5) and state of charge (SoC) calculation (1.6). The binary variables $Y_{(st,t)}$ and $X_{(st,t)}$ are defined as a charging or discharging decision.

$$P_{Ch\ (st,t)} \le P_{Ch(st,t)}^{Max}\ Y_{(st,t)}, \forall t;\ \forall st \tag{1.2}$$

$$P_{Dch\ (st,t)} \le P_{Dch(st,t)}^{Max}\ X_{(st,t)}, \forall t;\ \forall st \tag{1.3}$$

$$Y_{(st,t)} + X_{(st,t)} \le 1, Y_{(st,t)}\ binary, \forall t;\ \forall st \forall t;\ \forall st \tag{1.4}$$

$$SoC_{(st)}^{Min} \le SoC_{(st,t)} \le SoC_{(st)}^{Max}, \forall t;\ \forall st \tag{1.5}$$

$$SoC_{(st,t)} = SoC_{(st,t-1)} + \eta_{Ch(st)}\ P_{Ch\ (st,t)} - 1/\eta_{Dch(st)} \big(P_{Dch\ (st,t)} \big), \forall t;\ \forall st \tag{1.6}$$

The active and reactive power constraints for DER, including RES, are defined by equations (1.7) to (1.10).

$$P_{DG\ (g,t)} \le P_{DG(g,t)}^{Max}, \forall t;\ \forall g \tag{1.7}$$

$$P_{DG\ (g,t)} = P_{DG(g,t)}^{Max}, \forall t;\ \forall g \in \{Wind\ and\ PV\} \tag{1.8}$$

$$P_{DG(g,t)}^{Cut} \le P_{DG\ (g,t)}, \forall t;\ \forall g \tag{1.9}$$

$$0 < Q_{DG\ (g,t)} \le \big(P_{DG\ (g,t)} - P_{DG(g,t)}^{Cut} \big) \tan \varphi_{(g,t)},\ \forall t;\ \forall g \tag{1.10}$$

The load shedding and reactive power are determined by equations (1.11) and (1.12).

$$P_{L(l,t)}^{Shed} \le P_{L\ (l,t)}, \forall t;\ \forall l \tag{1.11}$$

$$Q_{L\ (l,t)} = \big(P_{L\ (l,t)} - P_{L(l,t)}^{Shed} \big) \tan \varphi_{(l,t)},\ \forall t;\ \forall l \tag{1.12}$$

The power exported at each instant *t* cannot exceed the defined maximum limit (1.13).

$$P_{Grid(t)}^{Export} \le P_{Grid(t)}^{Max}, \quad \forall t \tag{1.13}$$

The active and reactive power balance on the bus *i* in each delivery period *t* is represented by equations (1.14) and (1.15).

$$V_{i(t)}^2\ G_{ii} + V_{i(t)} \sum_{j \epsilon y^1} \Big(V_{j(t)}\ \big(G_{ij}\ \cos\big(\theta_{i(t)} - \theta_{j(t)}\big) - B_{ji}\ \sin\big(\theta_{i(t)} - \theta_{j(t)}\big)\big)\Big) = \sum_{g=1}^{N_{DG}^i} \big(P_{DG(g,t)}^i - P_{DG(g,t)}^{Cut,i} \big) - P_{Grid(g,t)}^{Export,i} + \sum_{st=1}^{N_{storage}^i} \big(P_{Dch(st,t)}^i - P_{Ch(st,t)}^i \big) - \sum_{i=1}^{N_{load}^i} \big(P_{Load(l,t)}^i \big),\ \forall t, \forall i, \forall j \tag{1.14}$$

$$-V_{i(t)}^2\ B_{ii} + V_{i(t)} \sum_{j \epsilon y^1} \Big(V_{j(t)}\ \big(G_{ij}\ \sin\big(\theta_{i(t)} - \theta_{j(t)}\big) - B_{ji}\ \cos\big(\theta_{i(t)} - \theta_{j(t)}\big)\big)\Big) = \sum_{g=1}^{N_{DG}^i} \big(Q_{DG(g,t)}^i \big) - Q_{Grid(t)}^{Export,i} - \sum_{i=1}^{N_{load}^i} \big(Q_{Load(l,t)}^i \big),\ \forall t, \forall i, \forall j \tag{1.15}$$

The voltage magnitude is determined by equation (1.16). On the reference bus, the voltage assumes a fixed value.

$$V_{i(t)}^{min} \le V_{i(t)} \le V_{i(t)}^{min}, \forall t;\ \forall i \tag{1.16}$$

B. Reserve-only market

The reserve market model consists of the procurement of upward and downward capacity reserve, which is given by the following equations. Note that DW and UP indexes refer to the downward and upward reserve capacities respectively. The objective function is given by (2.1)

$$Minimize\ f = \sum_{t=1}^{T} \Big[\sum_{g=1}^{N_{DG}} \big(P_{DG(g,t)}^{UP}\ \pi_{DG\ (g,t)}^{UP} + P_{DG(g,t)}^{DW}\ \pi_{DG\ (g,t)}^{DW} \big) + \sum_{st=1}^{N_{Storage}} \big(P_{Dch(st,t)}^{UP}\ \pi_{Dch\ (st,t)}^{UP} + P_{Dch(st,t)}^{DW}\ \pi_{Dch\ (st,t)}^{DW} + P_{Ch(st,t)}^{UP}\ \pi_{Ch\ (st,t)}^{UP} + P_{Ch(st,t)}^{DW}\ \pi_{Ch\ (st,t)}^{DW} \big) \Big] \tag{2.1}$$

where $P_{DG(g,t)}^{UP}$ and $P_{DG(g,t)}^{DW}$ correspond to the upward and downward reserve of generator *g* in each time *t*, respectively. $\pi_{DG\ (g,t)}^{UP}$ and $\pi_{DG\ (g,t)}^{DW}$ represent the costs associated with the offered capacity. The energy values scheduled in the energy market $P_{DG(g,t)}^{Energy}$ are discounted from the maximum production capacity of generator *g*, resulting in the upward reserve.

$$0 < P_{DG(g,t)}^{UP} \le P_{DG(g,t)}^{Max} - P_{DG(g,t)}^{Energy}, \forall t;\ \forall g \tag{2.2}$$

On the other hand, the energy scheduled limits the downward reserve $P_{DG(g,t)}^{DW}$.

$$0 < P_{DG(g,t)}^{DW} \le P_{DG(g,t)}^{Energy}, \forall t;\ \forall g \tag{2.3}$$

The BESS operation meets constraints presented in equations (2.4) to (2.6). Equation (2.4) refers to the power limit for charging for the UP and DW reserve, considering the maximum charging capacity and the energy committed in the energy market. The constraint in (2.5) is analogous to (2.4), however, it refers to the discharging power for DW and UP reserve. The SoC of the BESS is determined through equation (2.6). Note that for the BESS modelling to be completed, equations (1.4) and (1.5) must be included.

$$P_{Ch\,(st,t)} - P^{UP}_{Ch(st,t)} + P^{DW}_{Ch(st,t)} \le P^{Max}_{Ch(st,t)}\, Y_{(st,t)}, \forall t;\ \forall st \tag{2.4}$$

$$P_{Dch\,(st,t)} + P^{UP}_{Dch(st,t)} - P^{DW}_{Dch(st,t)} \le P^{Max}_{Dch(st,t)}\, X_{(st,t)}, \forall t;\ \forall st \tag{2.5}$$

$$SoC_{(st,t)} = SoC_{(st,t-1)} + \eta_{Ch(st)}\left(P_{Ch\,(st,t)} - P^{UP}_{Ch(st,t)} + P^{DW}_{Ch(st,t)}\right) - \frac{1}{\eta_{Dch(st)}}\left(P_{Dch\,(st,t)} + P^{UP}_{Dch(st,t)} - P^{DW}_{Dch(st,t)}\right), \forall t;\ \forall st \tag{2.6}$$

Finally, the upward $R^{UP}_{(t)}$ and downward $R^{DW}_{(t)}$ reserve balance constraints are given by equations (2.7) and (2.8).

$$\sum_{g=1}^{N_{DG}}\left(P^{UP}_{DG(g,t)}\right) + \sum_{st=1}^{N_{storage}}\left(P^{UP}_{Ch(st,t)} + P^{UP}_{Dch(st,t)}\right) = R^{UP}_{(t)}, \forall t \tag{2.7}$$

$$\sum_{g=1}^{N_{DG}}\left(P^{DW}_{DG(g,t)}\right) + \sum_{st=1}^{N_{storage}}\left(P^{DW}_{Ch(st,t)} + P^{DW}_{Dch(st,t)}\right) = R^{DW}_{(t)}, \forall t \tag{2.8}$$

C. Joint energy and reserve market

The economic dispatch of the joint market results from the combination of the formulations presented in subsections A and B into a single formulation. The objective function is similar in structure to the one presented in (1.1), additionally, it considers the variables and constraints for upward and downward reserve from (2.1). For the sake of simplicity, the objective function is given by

$$\begin{aligned} Minimize\ f = \sum_{t=1}^{T}\Big[&\sum_{g=1}^{N_{DG}}\big(P_{DG\,(g,t)}\,\pi_{DG\,(g,t)} + P^{Cut}_{DG(g,t)}\,\pi^{Cut}_{DG\,(g,t)} + P^{UP}_{DG(g,t)}\,\pi^{UP}_{DG\,(g,t)} + P^{DW}_{DG(g,t)}\,\pi^{DW}_{DG\,(g,t)}\big) - P^{Export}_{Grid\,(t)}\,\pi^{Export}_{Grid\,(t)} + \\ &\sum_{l=1}^{N_{load}}\big(P^{Shed}_{L(l,t)}\,\pi^{Shed}_{L\,(l,t)}\big) + \sum_{st=1}^{N_{Storage}}\big(P_{Dch\,(st,t)}\,\pi_{Dch\,(st,t)} - P_{Ch\,(st,t)}\,\pi_{Ch\,(st,t)} + P^{UP}_{Dch(st,t)}\,\pi^{UP}_{Dch\,(st,t)} + \\ &P^{DW}_{Dch(st,t)}\,\pi^{DW}_{Dch\,(st,t)} + P^{UP}_{Ch(st,t)}\,\pi^{UP}_{Ch\,(st,t)} + P^{DW}_{Ch(st,t)}\,\pi^{DW}_{Ch\,(st,t)}\big)\Big] \end{aligned} \tag{3.1}$$

The objective function is subjected to the energy (1.2)) to (1.13) and reserve (2.1) to (2.8) constraints applied in the single energy and reserve market models, respectively.

III. CASE STUDY

A case study illustrating the applicability and performance of the proposed analysis, accounting for a variety of BESS participation in different markets is presented in this section. In addition, an analysis of the flexibility of an energy community is made, based on a virtual battery (VB) model.

A. Network characterization

A 37-bus distribution network (Fig. 1) is considered as a test case. It contains 1 bus representing the energy import from the upstream connection and 27 DER units (22 photovoltaic (PV), 2 wind power plants (WP) and 3 combined heat and power units (CHP)). A high penetration DER projection scenario is considered [15]. 22 loads are spread throughout the grid, accounting for variable consumption throughout the year considering the four seasons' profiles.

B. Resources characterization

In the first case, the network has 14 BESS units installed as shown in Figure 1. Table I presents a summary of available capacity and resource costs for energy, upward and downward reserve bids.

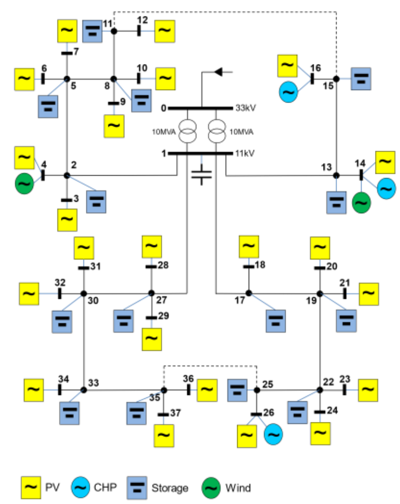

Figure 1. Electrical distribution network diagram.

TABLE I. AVAILABILITY AND COSTS ASSOCIATED WITH THE RESOURCES AVAILABLE IN THE DISTRIBUTION NETWORK.

Energy Resources	**Total Availability (MW) Min - Max**	**Costs (m.u./MW) Min-Max**		
		Energy	***Reserve UP***	***Reserve DW***
External supplier	35	0,1	0,0120 - 0,015	0,0059 - 0,0068
CHP	1,5	0,01 - 0,03	0,0120 - 0,015	0,0049 - 0,0063
WP	2,5	0	-----	-----
PV	0,071 - 5,923	0	-----	-----
BESS	Charge	-1,4	0	0

In terms of production costs, a zero price was associated with RES production, to simulate the priority of these resources under feed-in tariffs. Higher costs were related to the CHP production due to its non-renewable nature. The resource with a higher price corresponds to the external supplier. The costs associated with the reserve market were defined according to their average proportion to the energy market, based on MIBEL prices in 2019 [16]. Table II and Table III presents the load forecasts and the consequent UP and DW reserve requirements.

TABLE II. LOADS AND RESERVE REQUIREMENTS CHARACTERISTICS.

Consumption	Load (MW) Min - Max	Reserve UP (MW) Min - Max	Reserve DW (MW) Min - Max	Energy Not Supplied (m.u./MW)
	1,633 - 24,944	0,049 - 0,748	0,024 - 0,04899	4,5

In a second scenario, the performance of consumption flexibility on bus 18 is analyzed. For this purpose, a virtual BESS is added to this bus to describe the behavior of this energy community [17].

The mathematical formulation of BESS behaviour can be used to measure the flexibility of a given consumer, based on the concept of virtual generation aggregated in a single bus [18]. The consumption forecast $P_{b\,(c,t)}$ in an energy community (c) is defined as a baseline. Positive flexibility $P^{Pos}_{flx\,(c,t)}$ is the capacity of this community to increase its consumption concerning the baseline (charging) (4.1). Likewise, the negative flexibility $P^{Neg}_{flx\,(c,t)}$ is the consumption reduction in relation to the baseline or even generation (discharging) (4.2).

$$\left|P^{Pos}_{flx\,(c,t)} - P_{b\,(c,t)}\right| \geq P^{VBESS}_{Ch\,(vst,t)}\, Y_{(st,t)}, \forall t;\ \forall st \qquad (4.1)$$

$$\left|P_{b\,(c,t)} - P^{Neg}_{flx\,(c,t)}\right| \geq P^{VBESS}_{Dch\,(vst,t)} * X_{(st,t)}\,, \forall t;\ \forall st \qquad (4.2)$$

where $P^{VBESS}_{Ch\,(vst,t)}$ corresponds to the power of the charging offer of the VB (st) and $P^{VBESS}_{Dch\,(vst,t)}$ to the power of the discharging offered. To calculate the baseline and the possible flexibilities of the VB, the device scenarios are described in Table III and based on [17], [19].

TABLE III. RESOURCES AND DEVICES CONSIDERED IN THE STUDY OF FLEXIBILITY IN THE COMMUNITY.

Resources/Appliances		Supplied/Consumed Power (MW) Min-Max
Home appliances	*Clothes dryer*	0 – 0,084
	Dishwasher	0 – 0,24
	Washing machine	0 – 0,12
Electric Water Heater		0 – 0,24
Air Conditioning		0 – 0,36
Electric Vehicles		-0,24 – 0,24
BESS		-0,1 – 0,1
PV		-0,17 – 0

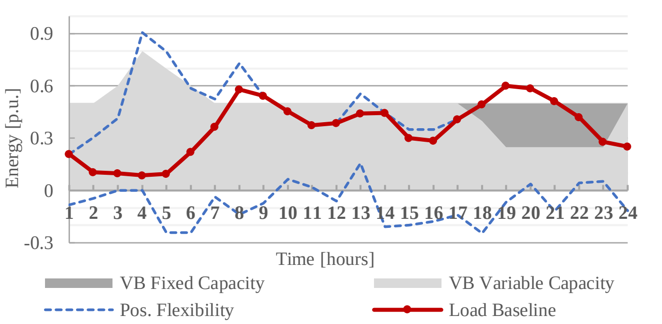

Figure 2. Consumption flexibility in the energy community and VB capacity strategies.

Fig. 2 presents the community consumption baseline (represented in red) and the positive and negative flexibilities (in dashed blue) according to the definition established in (4.1) and (4.2). To define the SoC limits of the VB, two ways of operation were analysed: i) fixed capacity and ii) variable capacity. In i), a fixed SoC of 0.5 MW was considered.

C. Results

This section presents the dispatch results for the different market models under study. Table IV shows the annual results of global operating costs, divided by four seasons.

TABLE IV. ANNUAL RESULTS OF GLOBAL OPERATING COSTS.

DISPATCH MODEL	Operations Costs (m.u./MW)				
	Autumn	*Spring*	*Summer*	*Winter*	*TOTAL*
Energy	1697,63	1748,58	1770,40	2252,24	**7468,85**
Reserve	10,23	10,47	10,64	12,323	**43,66**
Joint Energy + Reserve	1675,28	1726,55	1760,93	2328,14	**7490,91**
Sequential Energy + Reserve	1697,63	1749,31	1782,81	2357,51	**7587,26**

The measured energy consumption was higher than the RES production in all periods of simulation, during all seasons of the year, except for summer. Thus, summer was the only season of the year when there was surplus production that could be stored.

The lack of surplus had a limitation effect on the BESS operation, both in the energy market and in the sequential market, because, in the sequential market, the reserve dispatch was reliant on the energy dispatch result. This situation prevented the BESS to take advantage of the multiservice operation.

The joint energy and reserve market has lower global operating costs than the sequential market in all seasons. This can be explained by a more advantageous BESS operation, namely in the simultaneous participation in both markets. This evidence can be confirmed by the graphs presented in Fig. 3 and Fig. 4, the BESS offers on the summer day of minimum load – the one with the greatest surplus of RES production.

In both models, when there is a RES surplus, BESS is charging. However, the consistent difference lies in the discharging strategy adopted: i) Sequential Market: the amount of energy discharged depends on the BESS state of charge and only occurs at times of peak consumption. ii) Joint Market: there is a greater nominal amount of energy discharged throughout the day.

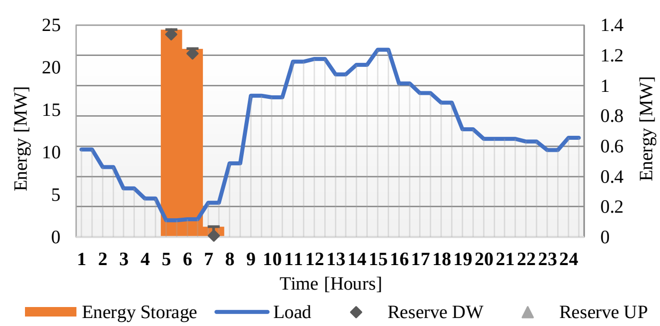

Figure 3. Joint Market BESS charging bids.

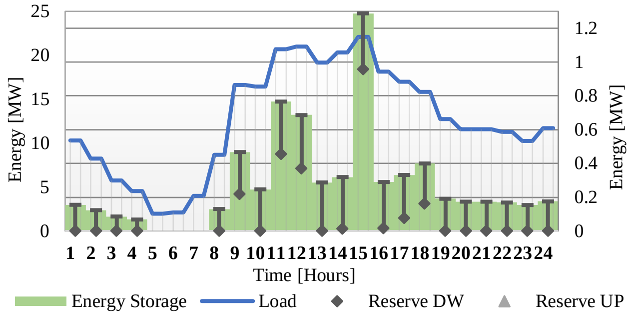

Figure 4. Joint Market BESS discharging bids.

This discharging strategy is proportional to the consumption on the distribution grid. It should also be noted that there is a greater amount of energy discharged than that which is charged. This happens because, in this model, there is a simultaneous decision on the offers to be made for energy and reserve. To this extent, BESS can offset energy offload offers with Reserve DW offers in the same proportion, even when their SoC does not allow them to do so. This makes it possible to adopt a more advantageous strategy, which implies an increase in revenue.

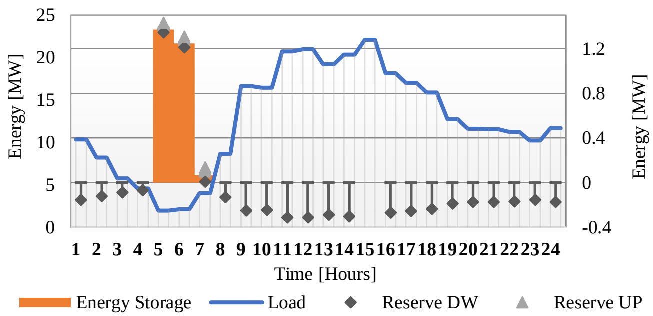

Figure 5. Sequential Market for BESS charging bids.

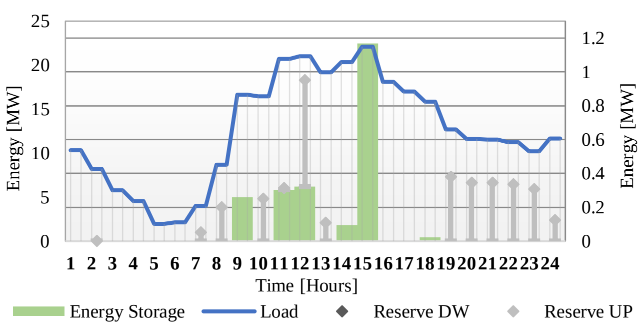

Figure 6. Sequential Market for BESS discharging bids.

The graphs in Fig. 7 and Fig. 8 represent the results of a virtual battery operation in a consumer community for the two distinct capacity scenarios: variable capacity and fixed capacity. The data also refers to the minimum load on a summer day.

The most advantageous strategy was the VB parameterization with variable SoC as shown in Fig. 7. This strategy allowed a reduction in distribution operating costs concerning the fixed capacity scenario. A variable capacity increases the controllability of the virtual BESS by the community manager: a capacity increase, at a certain moment, increases the probability of charging at that moment, while a capacity decrease maximizes the probability of discharging.

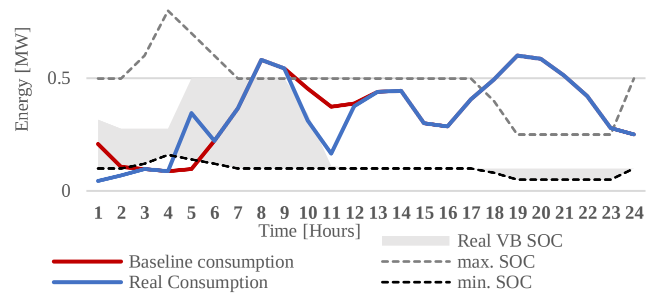

Figure 7. Energy community results - VB variable capacity.

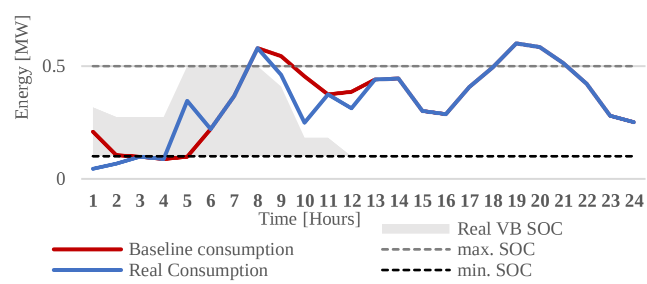

Figure 8. Energy community results - VB fixed capacity.

This BESS service differs from the conventional operation of battery storage systems present in the distribution grid. The results show that the VB has greater flexibility and greater operating possibilities, in the energy market, than conventional BESS. On the same simulation day, it has a discharging at hour 13, something that does not happen with the other BESS. This is also verified for other days in other seasons of the year, even when there is no renewable surplus.

IV. Conclusions

In this work, different market models were addressed, accounting for BESS participation in multiservice, namely energy and reserve. The impact of the BESS operation on the grid operation was also assessed, showing that its participation in the system increases when there is a surplus of renewables generation.

Nevertheless, the results show that the joint market is more advantageous for the BESS than the single or sequential energy and reserve market. The simultaneous determination of energy and reserve provides BESS the ability to correlate both offers for the time horizon period.

The ability of energy communities to model members' flexibility as a virtual BESS, open the doors to the establishment of profitability comparisons between the physical and virtual BESS operation in the energy and reserve markets. Thus, it is concluded that the virtual BESS allows greater controllability, thanks to its variable, flexible and operating capacity. This can promote more advantages for the network operation.

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