Addressing Unfeasibilities of Energy Storage Systems Participating in Energy and Reserve Markets

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***Abstract*— Optimization algorithms formulated to define the joint participation of Energy Storage Systems (ESSs) in energy and reserve markets often lead to unfeasibilities related to the available energy stored in the ESS, particularly if a relatively long-time horizon is considered (e.g., 24 hours). This paper addresses this issue and proposes an ESS model that assigns a specific amount of energy for up or down reserve provision according to the needs of ESS operator. Generally, ESSs do not participate on their own in the aforementioned markets, but rather, they usually operate jointly with stochastic non-dispatchable Renewable Energy Sources (RESs) in the form of a Virtual Power Plant (VPP). The proposed model allows operators to avoid possible unfeasibilities, and the potential penalties resulting from deviating from the day-ahead market (DAM) and secondary reserve market (SRM) offers. The model is implemented for a VPP consisting of a wind farm, a solar PV plant, and an ESS. The effectiveness of the model for bidding in joint markets is validated by several case studies.**

Keywords—Energy storage systems, day-ahead market, reserve provision, virtual power plant

I. Introduction

The penetration of non-dispatchable Renewable Energy Sources (RESs) has experienced remarkable growth over the past few decades, paving the way toward a greener and more sustainable scenario for electric energy generation. However, the stochastic nature of their sources (wind and sun) implies RESs to be less reliable when having to ensure a certain amount of power injection over a sufficiently long time period. This makes RESs not competitive against large, dispatchable conventional generation (CG) when participating in energy and reserve markets, as failing to comply with the contracted power in the market will lead to penalties from the market operators.

Typically, the Transmission System Operator (TSO) is responsible for maintaining the security of the power system [1]. In the case of power unbalances due to, e.g., equipment outages or sudden load increase, the Frequency Containment Reserve (FCR) is the first one to act and is responsible for bringing the frequency back to steady-state conditions. After a few tens of seconds, automatic Frequency Restoration Reserve (aFRR), also known as Secondary Reserve (SR), comes into play to bring back the frequency to its reference value and maintain the area power interchange at the schedule point. The unit that wants to provide SR in the market needs to be qualified by the TSO, and the requirements differ between countries. In Spain, for instance, the main requirements are providing reserve for 15 min uninterruptedly in the resolution time of 1 hour and with a response time of 100 s. The requirement for providing the reserve for such a time period limits the possibility of RESs becoming SR service providers by themselves.

To mitigate the impact of the stochastic nature of RESs, and, therefore, to increase their competitiveness, a common solution that has been widely proposed is the combination of RESs and fast-responding Energy Storage Systems (ESSs). Moreover, ESSs show a great potential to provide a large number of ancillary services to the power grid in a fast and reliable way [2]. Combining stochastic RESs with ESSs in the form of a Virtual Power Plant (VPP) thus becomes apparent [3]. VPPs would allow stochastic RESs to compensate for their inherent power output variations and meet the provision requirement.

The ESSs are usually exempted from providing reserve in the literature [4]–[8], or, when considered as SR providers, simplified models [9]–[12] are used which impose unfeasibility issues and penalties in the real-time operation. In [4], a decision-making tool is proposed for VPP managers to participate in different energy and reserve markets. The optimization problems related to medium-term and short-term markets are jointly solved. However, the reserve provision by ESSs is not modeled in the paper. In [5], a price taker model is proposed for the participation of VPP in energy, reserve, and reactive power markets. The VPP includes CG, ESS, and interruptible load. However, the ESS cannot provide ancillary services to the market. A nonlinear model is proposed for the participation of price taker VPP in the energy and spinning reserve markets in [6]. The only asset that can provide reserve is CG, and the simulation model suffers from intractability issues. In [7], the VPP participation in the day-ahead market (DAM) for trading both energy and reserve is modeled by using a stochastic adaptive robust optimization problem. However, the reserve provision is modeled in a simple way and the reserve provision by ESSs is not modeled. Although the model provides an optimal solution when the reserve is activated in one direction, it does not guarantee operational feasibility for all possible reserve activation scenarios. In [8], the price taker VPP participation in the DAM, reserve, and real-time markets is optimized for finding the best bidding strategies in different markets. The reserve provision is only possible for CG and demand. Besides, operation unfeasibility or penalties in real-time operation is possible due to not considering all reserve activation scenarios.

In [9], a price maker VPP is considered to optimize the bidding strategy of ESS, RES, and demand in the DAM, reserve, and balancing markets. Although the paper considers ESS as a reserve provider, the model can lead to unfeasible operation scenarios in real-time due to not considering appropriate energy constraints for ESS. In [10], a bi-level price maker model is offered to maximize the VPP's total profit in the primary and secondary reserve market (SRM)s. However, the ESSs cannot provide both up and down reserve in the ancillary service markets. Moreover, the ESSs constraints that link different hours are not considered. In [11], a co-optimization method is proposed to model an urban VPP participation in the energy, ancillary services, and balance markets. Although the ESSs can provide the reserve, the reserve provision capability of ESSs is only limited by their discharging power but not by their energy. In [12], a price taker approach is considered to model the operation of thermal and electrical resources of VPP in the energy and reserve market. The paper does not consider reserve provision limitations of ESSs and suffers from accurate modeling when it comes to reserve activation time.

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To overcome the drawbacks in the literature listed above, in this work ESSs are modeled in such a way to address the unfeasibilities in providing reserve. The constraints related to interconnections of ESSs energy levels in different time periods are modified to consider the energy of ESSs for providing reserve in the real-time operation. In this regard, a specified amount of ESS energy is assigned only to provide up and down reserve. This amount can be tailored according to the needs VPP operator. Besides, reserve provision is defined for both charging and discharging states of ESSs.

The remainder of the paper is organized as follows. Section II illustrates the potential unfeasibility issues of ESSs providing SR. The VPP formulation in the DAM and SRM is proposed in Section III. The numerical results of a case study considering a VPP comprising RESs and an ESS are presented and discussed in Section IV. Finally, the conclusion is drawn in Section V.

II. Problem Clarification

Fig. 1 illustrates the unfeasibility issue in the real-time operation of ESSs that can arise by considering SR independently, if the problem is formulated as in [9]–[12]. Three sample hours of schedule are chosen for the example. The power that the ESS operator needs to provide to the market is according to the blue line in Fig. 1.a). Besides, the red and blue dashed lines in Fig. 1.a), respectively, show the up and down reserve that the ESS operator needs to provide if the system operator calls for reserve. It is assumed that the ESS operator bids for both up and down reserves but only needs to provide up reserve, which is shown by the dashed green line in Fig. 1.a), within three hours of schedule. Fig. 1.b) demonstrates the scheduled energy of ESS, shown by the black line, to its corresponding power for these three hours. The energy that should be kept for up and down reserves, represented by the red and blue dashed lines, respectively, is assigned for each period without considering the reduction or increase of energy by activation of reserve in real-time. The purple-green dashed line shows the actual energy of ESS in real-time. When the reserve is activated, the slope of ESS energy reduction increases. This leads to less energy than expected for the beginning of the next hour of the schedule. If the ESS operator has to activate the up reserve for the next hours, as the example shows, the energy of ESS in real-time should be less than its minimum energy, which is not possible. As Fig. 1.b) shows, the energy of ESS goes lower than its minimum value at the end of hour 2. It is worth mentioning that the unfeasibility issue may arise when the disturbances causing the reserve activation is not too large. Indeed, the system operator would intervene and redispatch generation units in case of large significant disturbances, possibly modifying the posterior market schedule.

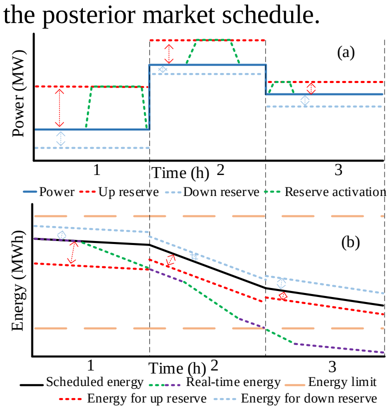

Fig. 1. Unfeasibility issue related to reserve provision of ESSs.

III. Formulation

A. Nomenclature

This section presents the notation used to formulate the VPP model in the DAM and SRM.

Indexes and sets:	
$r \in R$	Set of RESs
$s \in S$	Set of ESSs
$t \in T$	Set of time periods
Ξ	Set of decision variables of DAM and SRM
Parameters:	
C_r^R	Operation and maintenance costs of RES r [€/MWh]
C_s	Installation and expected operational costs of ESS s [€]
$\underline{E}_s/\overline{E}_s$	Lower/upper bound of ESS s energy level [MWh]
M_s	Slope of the linear approximation of the expected life of ESS s as a function of the cycles [-]
$\underline{P}_{r,t}/\overline{P}_{r,t}$	Lower/upper bound of RES r power production in time period t [MW]
$\underline{P}_s^{Ch}/\overline{P}_s^{Ch}$	Lower/upper bound of charging capacity of ESS s [MW]
$\underline{P}_s^{De}/\overline{P}_s^{De}$	Lower/upper bound of discharging capacity of ESS s [MW]
$\underline{R}_{r(s)}^{SR}/\overline{R}_{r(s)}^{SR}$	Down/up SR ramp rate of RES r (ESS s) [MW/min]
T^{SR}	Required time for SR action [min]
$\underline{\alpha}_s/\overline{\alpha}_s$	Lower/upper bound multiplier of ESS s at last period in schedule [-]
Δt	Duration of time periods [hour]
γ_s	Self-discharge value of ESS s per an hour period [%]
η_s^{Ch}/η_s^{De}	Charge/discharge efficiency of ESS s [%]
λ_t^{DA}	DAM price in time period t [€/MWh]
$\lambda_t^{SR,\uparrow}/\lambda_t^{SR,\downarrow}$	SRM up/down price in time period t [€/MW]
χ_t	Coefficient of up to down SR requested by system operator in time period t
κ	Coefficient of up reserve traded in the market compared to the total power capacity of VPP.
Continuous variables:	
c_s^{Deg}	Degradation cost per cycle of ESS s [€]
$e_{s,t}$	Energy stored in ESS s in time period t [MWh]
$p_{r(s),t}$	Active power output of RES r (ESS s) in time period t [MW]
$p_{s,t}^{Ch}/p_{s,t}^{De}$	Charging/discharging power level of ESS s in time period t [MW]
p_t^{DA}	Total power traded in the DAM in time period t [MW]
$r_t^{SR,\uparrow},r_t^{SR,\downarrow}$	Total up/down reserve traded in the SRM in time period t [MW]
$r_{r(s),t}^{SR,\uparrow}/r_{r(s),t}^{SR,\downarrow}$	Up/down SR provided by RES r (ESS s) in time period t [MW]
$r_{s,t}^{SR,Ch,\uparrow}/r_{s,t}^{SR,Ch,\downarrow}$	Up/down SR provided by ESS s in charging state in time period t [MW]
$r_{s,t}^{SR,De,\uparrow}/r_{s,t}^{SR,De,\downarrow}$	Up/down SR provided by ESS s in discharging state in time period t [MW]
$\sigma_s^{SR,\uparrow}/\sigma_s^{SR,\downarrow}$	Share of ESS s energy capacity allocated for providing up/down SR [%]
Binary variables:	
$u_{s,t}$	Binary variable used to prevent the simultaneous charging and discharging of ESS s in time period t [0/1]
$u_{r,t}$	Binary variable to commit the RES r in time period t [0/1]

$u_{r,t}^{SR}$	Binary variable used to prevent the simultaneous providing up and down SR by RES *r* in time period *t* [0/1]
$u_{s,t}^{SR,Ch}/u_{s,t}^{SR,De}$	Binary variables used to prevent the simultaneous providing up and down SR by ESS *s* in charging/discharging state in time period *t* [0/1]

B. VPP objective function

The objective function (1) maximizes the benefits that VPP can obtain by selling energy in the DAM and selling up/down reserve in the SRM minus costs. The costs include the maintenance and operation costs of RESs and the battery degradation cost.

$$\max_{\Xi} \sum_{t\in T}\left[\begin{array}{l}\lambda_t^{DA} p_t^{DA}\Delta t+\lambda_t^{SR,\uparrow} r_t^{SR,\uparrow}\\ +\lambda_t^{SR,\downarrow} r_t^{SR,\downarrow}-\sum_{r\in R} C_r^R p_{r,t}\Delta t\end{array}\right]-\sum_{s\in S} c_s^{D\mathrm{eg}} \tag{1}$$

C. RES constraints

The RESs power output and reserve are constrained by equations (2)-(6). Constraints (2)-(3) assign the maximum and minimum power provided by RESs, respectively. The binary variable $u_{r,t}$ assures the output power of RESs to be zero when they are off. Constraints (4)-(5) limit the up/down reserve that each RES can provide when the system operator calls for the up or down reserve. The binary variable $u_{r,t}^{SR}$ does not allow providing both up and down reserve at the same time. Constraint (6) shows the nature of binary variables.

$$p_{r,t}+r_{r,t}^{SR,\uparrow}\le\bar{P}_{r,t}u_{r,t} \qquad \forall r\in R,\forall t\in T \tag{2}$$

$$\underline{P}_{r,t}u_{r,t}\le p_{r,t}-r_{r,t}^{SR,\downarrow} \qquad \forall r\in R,\forall t\in T \tag{3}$$

$$r_{r,t}^{SR,\uparrow}\le T^{SR}\bar{R}_r^{SR}u_{r,t}^{SR} \qquad \forall r\in R,\forall t\in T \tag{4}$$

$$r_{r,t}^{SR,\downarrow}\le T^{SR}\underline{R}_r^{SR}(1-u_{r,t}^{SR}) \qquad \forall r\in R,\forall t\in T \tag{5}$$

$$u_{r,t},u_{r,t}^{SR}\in\{0,1\} \qquad \forall r\in R,\forall t\in T \tag{6}$$

D. ESSs constraints

The ESSs formulation is presented in (7)-(25). The constraints (7)-(10) limit the charging and discharging capability of ESSs considering providing SR. The binary variable $u_{s,t}$ prevents simultaneous charging and discharging of ESSs. Constraints (11)-(14) define the SR ramp capability of ESSs. Equations (11)-(14) provide the up or down reserve activation possibility for both charging and discharging states. The binary variables $u_{s,t}^{SR,Ch}$ and $u_{s,t}^{SR,De}$ prevents simultaneous up and down SR provision by ESSs in the charging and discharging states, respectively. The output power of ESSs is assigned by (15). The final up/down SR provided by the ESSs are calculated by (16)-(17). The energy level of ESSs is related to their power by (18). A specified amount of ESSs energy is assigned only to provide up and down reserve by (19)-(20). Constraint (19) limits this specified amount of energy considering the maximum up reserve is called on for all periods. Constraint (20) is the down reserve case of (19). The energy of ESSs is limited by (21)-(23) considering the value of energy assigned to provide the SR reserve. The upper and lower limits for the last period are assigned by (22)-(23) at a specific value to energy not be completely depleted or to be full at the beginning of the next period. The ESSs degradation cost is defined in (24). The nature of binary variables is defined in (25). It is worth mentioning that the ESSs formulation presented in this paper solves the drawback in the literature [9]–[12], which is explained in Section II. The unfeasibility issues are solved by separating ESSs energy equations (18)-(23) for offering power and reserve. Therefore, the energy for the provision of power and reserve is considered, and the formulation does not lead to less energy stored in ESSs as expected in the real-time operation.

$$p_{s,t}^{Ch}+r_{s,t}^{SR,Ch,\downarrow}\le\bar{P}_s^{Ch}u_{s,t} \qquad \forall s\in S,\forall t\in T \tag{7}$$

$$\underline{P}_s^{Ch}u_{s,t}\le p_{s,t}^{Ch}-r_{s,t}^{SR,Ch,\uparrow} \qquad \forall s\in S,\forall t\in T \tag{8}$$

$$p_{s,t}^{De}+r_{s,t}^{SR,De,\uparrow}\le\bar{P}_s^{De}(1-u_{s,t}) \qquad \forall s\in S,\forall t\in T \tag{9}$$

$$\underline{P}_s^{De}(1-u_{s,t})\le p_{s,t}^{De}-r_{s,t}^{SR,De,\downarrow} \qquad \forall s\in S,\forall t\in T \tag{10}$$

$$r_{s,t}^{SR,De,\uparrow}\le T^{SR}\bar{R}_s^{SR}u_{s,t}^{SR,De} \qquad \forall s\in S,\forall t\in T \tag{11}$$

$$r_{s,t}^{SR,De,\downarrow}\le T^{SR}\underline{R}_s^{SR}(1-u_{s,t}^{SR,De}) \qquad \forall s\in S,\forall t\in T \tag{12}$$

$$r_{s,t}^{SR,Ch,\downarrow}\le T^{SR}\underline{R}_s^{SR}u_{s,t}^{SR,Ch} \qquad \forall s\in S,\forall t\in T \tag{13}$$

$$r_{s,t}^{SR,Ch,\uparrow}\le T^{SR}\bar{R}_s^{SR}(1-u_{s,t}^{SR,Ch}) \qquad \forall s\in S,\forall t\in T \tag{14}$$

$$p_{s,t}=p_{s,t}^{De}-p_{s,t}^{Ch} \qquad \forall s\in S,\forall t\in T \tag{15}$$

$$r_{s,t}^{SR,\uparrow}=r_{s,t}^{SR,De,\uparrow}+r_{s,t}^{SR,Ch,\uparrow} \qquad \forall s\in S,\forall t\in T \tag{16}$$

$$r_{s,t}^{SR,\downarrow}=r_{s,t}^{SR,De,\downarrow}+r_{s,t}^{SR,Ch,\downarrow} \qquad \forall s\in S,\forall t\in T \tag{17}$$

$$e_{s,t}=(1-\gamma_s)(e_{s,(t-1)})+p_{s,t}^{Ch}\eta_s^{Ch}\Delta t-\frac{p_{s,t}^{De}\Delta t}{\eta_s^{De}} \qquad \forall s\in S,\forall t\in T \tag{18}$$

$$\sum_{t\in T}\left(\frac{r_{s,t}^{SR,\uparrow}\Delta t}{\eta_s^{De}}\right)\le\sigma_s^{SR,\uparrow}(\bar{E}_s-\underline{E}_s) \qquad \forall s\in S \tag{19}$$

$$\sum_{t\in T}(r_{s,t}^{SR,\downarrow}\eta_s^{Ch}\Delta t)\le\sigma_s^{SR,\downarrow}(\bar{E}_s-\underline{E}_s) \qquad \forall s\in S \tag{20}$$

$$\underline{E}_s+\sigma_s^{SR,\uparrow}(\bar{E}_s-\underline{E}_s)\le e_{s,t}\le\bar{E}_s-\sigma_s^{SR,\downarrow}(\bar{E}_s-\underline{E}_s) \qquad \forall s\in S,\forall t\le T-1 \tag{21}$$

$$\underline{\alpha}_s(\underline{E}_s+\sigma_s^{SR,\uparrow}(\bar{E}_s-\underline{E}_s))\le e_{s,t} \qquad \forall s\in S,\forall t=T \tag{22}$$

$$e_{s,t}\le\bar{\alpha}_s(\bar{E}_s-\sigma_s^{SR,\downarrow}(\bar{E}_s-\underline{E}_s)) \qquad \forall s\in S,\forall t=T \tag{23}$$

$$c_s^{D\mathrm{eg}}=.01M_s\frac{C_s}{\bar{E}_s}\sum_{t\in T}p_{s,t}^{De}\Delta t \qquad \forall s\in S \tag{24}$$

$$u_{s,t},u_{s,t}^{SR,De},u_{s,t}^{SR,Ch}\in\{0,1\} \qquad \forall s\in S,\forall t\in T \tag{25}$$

E. Power and reserve balancing constraints:

Constraint (26) enforces the power balance equality for the VPP considering both RESs and ESSs. Up/down SR equalities are formulated in (27)-(28).

$$\sum_{r\in R}p_{r,t}+\sum_{s\in S}p_{s,t}=p_t^{DA} \qquad \forall t\in T \tag{26}$$

$$\sum_{r\in R}r_{r,t}^{SR,\uparrow}+\sum_{s\in S}r_{s,t}^{SR,\uparrow}=r_t^{SR,\uparrow} \qquad \forall t\in T \tag{27}$$

$$\sum_{r\in R}r_{r,t}^{SR,\downarrow}+\sum_{s\in S}r_{s,t}^{SR,\downarrow}=r_t^{SR,\downarrow} \qquad \forall t\in T \tag{28}$$

F. Power traded constraints:

The power and reserve traded to the main grid's constraints, which can be assigned according to the transmission line or power transformer capacity connected to the main bus of the network, are constrained by (29)-(30). The

TABLE I. VPP UNITS DATA.

Units	$\overline{P}_{r,t}$ (MW)	C_r^R (€/MWh)	$\underline{R}_r^{SR}/\overline{R}_r^{SR}$ (MW/min)
Wind farm	50	10	10
Solar PV	50	5	10

TABLE II. ESS DATA [13].

Technology	η_s^{Ch}/η_s^{De} (%)	$\overline{E}_s$ (MWh)	$\overline{P}_s^{Ch}/\overline{P}_s^{De}$ (MW)	$\underline{R}_s^{SR}/\overline{R}_s^{SR}$ (MW/min)	M_s	C_s (M€)	γ_s (%)	$\underline{\alpha}_s$	$\overline{\alpha}_s$
LI-ION	99	50	5	16.6	.001	15	.1	.09	1

TABLE III. THE COEEFICIENT OF UP TO DOWN RESERVE FOR A SAMPLE DAY IN MARCH 2014 [14].

Hour	χ_t	Hour	χ_t	Hour	χ_t	Hour	χ_t
1	1.17	7	1.80	13	1.20	19	1.20
2	1.17	8	1.80	14	1.20	20	1.80
3	1.25	9	1.80	15	1.20	21	1.80
4	1.25	10	1.80	16	1.20	22	1.14
5	1.25	11	1.20	17	1.20	23	1.14
6	1.25	12	1.20	18	1.20	24	1.33

amount of requested down reserve by the system operator is a proportion of up reserve for each period, which is modeled by (31). Constraint (32) sets the limit of up reserve traded in the market as a share of the total power capacity of VPP.

$$p_t^{DA} + r_t^{SR,\uparrow} \le \sum_{r\in R} \overline{P}_{r,t} + \sum_{s\in S} \overline{P}_s^{De} \qquad \forall t \in T \tag{29}$$

$$-\sum_{s\in S} \overline{P}_s^{Ch} \le p_t^{DA} - r_t^{SR,\downarrow} \qquad \forall t \in T \tag{30}$$

$$r_t^{SR,\uparrow} = \chi_t r_t^{SR,\downarrow} \qquad \forall t \in T \tag{31}$$

$$r_t^{SR,\uparrow} \le \kappa\left(\sum_{r\in R} \overline{P}_{r,t} + \sum_{s\in S} \overline{P}_s^{De}\right) \qquad \forall t \in T \tag{32}$$

IV. NUMERICAL RESULTS

The case study presented in this section considers a VPP in Spain composed of a wind farm, a solar PV plant, and an ESS, all connected to the same bus, and coupled to the network through a 50 MW line. The wind farm and solar PV characteristics are described in Table I, and their forecast power for a sunny day in March 2014 are shown in Fig. 2. The data of ESS are derived from [13] and are depicted in Table II. The required time for SR action is 15 min. The coefficient κ is assumed to be 0.15. The coefficient χ_t for the same day is described in Table III [14]. Two scenarios (cases) are considered, as follows:

- in Case 1, all VPP units can provide up/down reserve in the SRM; and
- in Case 2, only the ESS can provide SR.

The simulations are carried out using a Dell XPS with an i7-1165G7 processor, 2.8 GHz, and 16 GB of RAM using CPLEX solver in GAMS 38.3.0 [15].

A. Case studies

In Case 1, both RESs and ESS can provide up/down SR. Fig. 3 shows the power production of VPP's units for the planning horizon. Fig. 4 depicts the up/down SR of VPP's units in all periods. In Fig. 5, the power and SR which are traded in the electricity market are shown versus the electricity prices. The VPP operator bids to sell power and reserve in all periods as it is a power producer and does not contain demand. Between hours 11-18, ESS charges since the production power of PV is high and the electricity price is moderate. ESS discharges in the last hours of operation, hours 19-24, imposing higher electricity prices. In most periods, the wind

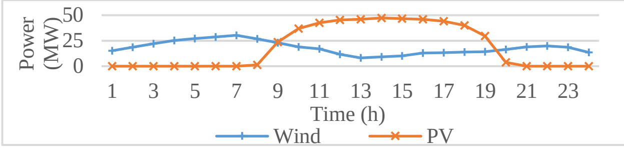

Fig. 2. Wind farm and PV plant power forecast.

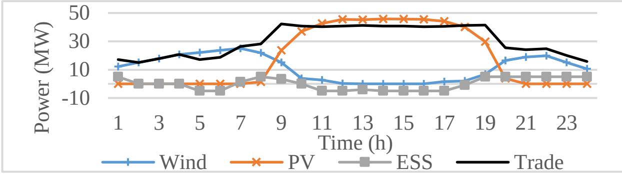

Fig. 3. Power production/consumption of VPP's units and traded power at each period (Case 1).

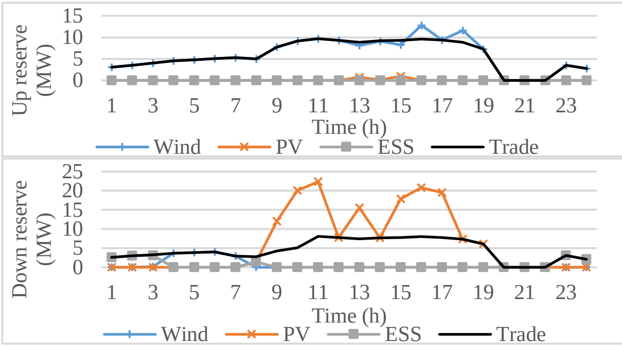

Fig. 4. Up/down and traded reserve provided by VPP's units at each period (Case 1).

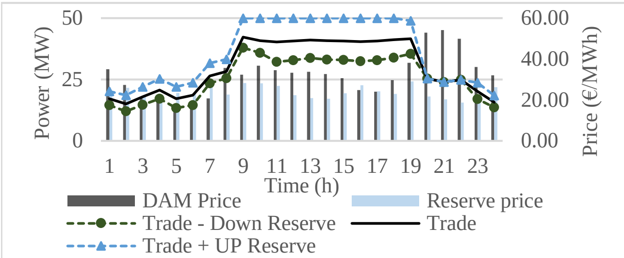

Fig. 5. Power and up/down reserve traded in the electricity market versus electricity price (Case 1).

provides up reserve as its operation cost is more than PV and ESS, so cutting its power leads to less total cost for the VPP. In some hours, e.g., hours 16 and 18, the up reserve that the wind producer can provide is less than the total up reserve traded in the market. This is due to the power limitation of the transmission line connected to the main network. In the case of down reserve provision, PV is the only technology that provides this reserve between hours 8-19 due to low operation cost. In hours 1-7 and 23-24, since the PV production is zero, Wind and ESS provide down reserve. Between hours 20-22, the VPP does not offer to sell both up/down reserve to the market as the power electricity price is much higher than the reserve price.

Fig. 6 demonstrates the power and energy of ESS at each period. Because ESS does not provide up reserve in the market, it can be operated at its minimum energy at hours 1-4 and 9-10. However, in the case of down reserve, a specified amount of energy is kept to provide reserve. As a result, the maximum energy that ESS can obtain is lower than its whole capacity (50 MWh), as shown by the energy line in Fig. 6. Limiting the energy of ESS for providing reserve is of utmost importance, as it solves the unfeasibility issues in the literature

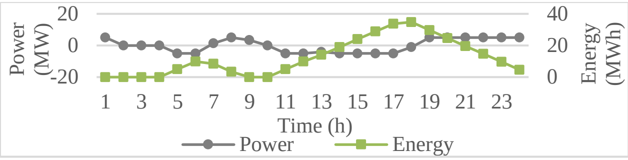

Fig. 6. Power and energy of ESS at each period (Case 1).

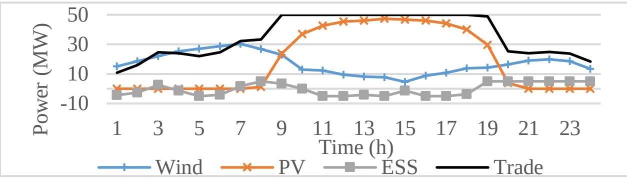

Fig. 7. Power production/consumption and traded power of VPP's units at each period (Case 2).

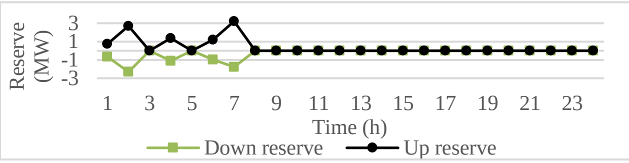

Fig. 8. Up/down reserve provided by ESS at each period (Case 2).

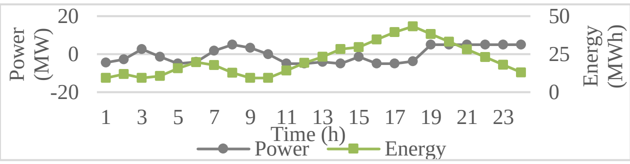

Fig. 9. Power and energy of ESS at each period (Case 2).

TABLE IV. VPP PROFIT IN DIFFERENT CASE STUDIES.

Case	*Reserve provision possibility*	*DAM revenue (€)*	*SRM revenue (€)*	*Cost (€)*	*Total profit (€)*
1	RESs and ESS	23,485	6,042	4,972	24,555
2	ESS	27,318	408	6,343	21,383

in which the reserve is calculated independently for each period.

As shown in Table IV, the total profit that VPP can obtain from the markets is 24,555 €. Most of the VPP income comes from DAM, which is 23,485 €.

In Case 2, to better understand ESS behavior in both up/down reserve provision, it is assumed that only ESS can provide reserve. Fig. 7 displays the power production of VPP units for this case. Up/down reserve provided by ESS is depicted in Fig. 8. The electricity prices are considered the same as in Case 1. In this case, as RESs cannot provide reserve, they can produce more power. As a result, it is more profitable for VPP to offer more power than Case 1 in the DAM. In this case, ESS provides both up/down reserve at hours 1-2, 4, 6-7. However, as the capacity of ESS is limited, it is mainly used for power arbitrage according to the total benefit of VPP. It is worth mentioning that the formulation in this paper assigns ESS energy for reserve provision according to the benefit that VPP can obtain. Therefore, it avoids assigning more energy than necessary for reserve provision. The minimum ESS energy is limited, according to Fig. 9, to provide up reserve in the SRM. For providing the down reserve, there is a limitation of maximum energy of ESS similar to Case 1 (compare Fig. 6 and Fig. 9).

According to Table IV, the total profit of VPP in Case 2 is 21,383 €, which is lower than in Case 1. This profit mostly comes from DAM, as participation of VPP in the SRM is limited. Besides, as VPP offers more power in the DAM, the operation cost of VPP units is more than in Case 1.

V. Conclusion

In this paper, the unfeasibility issues in providing reserve for ESSs are addressed by adjusting reserve constraints related to the power charging/discharging of ESSs and ESSs energy constraints. The energy to be saved for SR activation is the one needed to provide SR during the whole period. The simulations are implemented for a VPP consisting of a wind farm, a solar field, and an ESS that wants to participate in the joint DAM and SRM. The simulations show that the model can appropriately assign a limited amount of ESS energy for reserve provision to improve the economic benefit of VPP in the electricity markets. In future works, the authors plan to use and study real operation data on SR activation to enhance the formulation.

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