Operational Model of a RES Plant Coupled with Battery Storage Considering the Imbalance Settlement

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Abstract

In the European energy market, every market participant has a balance responsibility. With the expiration of feed-in tariffs, renewables are also becoming balance responsible. Since renewables, such as wind and solar, have very variable and not entirely predictable output, their imbalance management is highly challenging. This paper investigates the possibility of their imbalance management by installing battery energy storage within the renewable facility. The proposed bidding and balancing model, applicable to any type of distributed energy resource, is simulated for deterministic prices from the year 2020 and for the stochastic solar production scenarios.

Nomenclature

Sets and Indices

Ω^i	Set of breakpoints in linearized battery charging curve
Ω^j	Auxiliary set for linearization of soe
Ω^s	Set of scenarios
Ω^t	Set of time periods

Parameters

Δt	Time period [h]
η	Battery roundtrip efficiency
λ_t^{B}	Imbalance price [€/MWh]
λ_t^{DA}	Price of electricity on the DA market [€/MWh]
π_s	Probability of scenario realization
RES_t^{pred}	Planed production of RES [MW]
$RES_{t,s}^{\mathrm{r}}$	Real production of RES [MW]
$\underline{F_i}$	Coefficients for charging curve linearization
$\overline{P^{\mathrm{bat}}}$	Installed power of the battery inverter [MW]
$\overline{P^{\mathrm{ex}}}$	Grid connection power limit [MW]
$\underline{R_i}$	Coefficients for charging curve linearization
$\overline{SOE}$	Maximum BES capacity [MWh]

Variables

a	Binary variable, 1 if the battery is charging, 0 otherwise
b	Binary variable, 1 if the battery is charging, 0 otherwise
ch_t^{DA}	BES charging power at the DA market [MW]
$ch_{t,s}^{\mathrm{B}}$	Balancing power provided by BES charging [MW]
dis_t^{DA}	BES discharging power at the DA market [MW]
$dis_{t,s}^{\mathrm{B}}$	Balancing power provided by BES discharging [MW]
$res_{t,s}^{\mathrm{r}}$	Part of RES production injected into the grid [MW]
$e_{t,s}^{\mathrm{d}}$	Deviation of the BRP [MWh]
e_t^{mp}	Market position of the BRP [MWh]
$e_{t,s}^{\mathrm{r}}$	Realized production of the BRP [MWh]
$soe_{t,s,j}^{\mathrm{p}}$	State of energy at the segment j and scenario s [MWh]
$soe_{t,s}$	State of energy at scenario s [MWh]

1 Introduction

The energy market in Europe operates on a principle of balance responsibility. According to balance responsibility, each market participant is responsible for it's own imbalances and must be a part of a balance responsible party (BRP) [1]. A market participant has two options: to delegate responsibility to a third-party BRP or to manage imbalances on its own by creating new BRP.

Every BRP, during the planning stage, has to submit their planned production/consumption schedules to the Transmission System Operator (TSO). In real time, after an imbalance occurs, the TSO has to balance the system by activating reserve resources. After that, the TSO has to settle the imbalances of each BRP. Depending on the deviation of the planned production/consumption from the realized one, each BRP is charged an imbalance fee [2].

Even though there are three main methods for calculating the imbalance fee (single pricing, dual pricing, two price settlement) [3], [4], according to Article 55 of the Electricity Balancing GuideLine, each TSO should use the single imbalance pricing method [5]. Single imbalance pricing means that the positive and negative imbalances of a BRP are treated the same, regardless whether they help the system (decrease the total imbalances) or they harm the system (causing even higher imbalances). In other words, the single imbalance price means there is one price for both deviation directions. This method is also used in the Croatian balancing model [6]. Therefore, the single price method is considered in this paper.

At the beginning, the renewable integration had many challenges and barriers such as variable electricity price making returns highly uncertain thus repelling investments [7]. Therefore, it was necessary to develop a support policy that would attract investors in new technologies [8]. The main support scheme, during this first period of the renewables' integration, were feed-in tariff (FIT) [9], [10]. Under this scheme, the renewables were getting paid a fixed tariff for the injected energy into the grid and they were not responsible (and penalized) for their imbalances. Renewables under the FIT scheme were often part of special BRPs led by TSOs or market or market operators who took over their balancing responsibility. For example, in Croatia, the ECO BRP is created under the control of the Croatian Market Operator (HROTE) [11]. Since they did not pay their imbalance costs under this support policy, the renewables had no motivation to provide accurate forecasts as their day-ahead plans to their BRPs. Therefore, their BRPs had to pay high imbalance costs to the TSOs. For lower renewable penetration levels this was not a significant problem. However, when renewable share reached a certain threshold, this became problematic and costly for those BRPs.

The proposed idea was to keep the fixed payments but make them balance responsible. This was achieved by replacing FIT schemes with feed-in premium (FIP) support schemes [12]. Under the FIP, the renewables have the same obligations as conventional market participants: must be part of BRP, place the day-ahead schedules, and pay for imbalances. The only difference is the remuneration for generated electricity if wholesale prices are low (in this case they receive a premium on top of the wholesale price) [13]. The renewables balance responsibility is not a major challenge for big utilities holding both renewables and conventional generators as they can use conventional units' flexibility to cover renewable's imbalances. However, it is a huge challenge for companies with only uncontrollable and variable energy sources in their portfolio. Such companies, may have issues with high balancing costs if their forecasts are bad. This can significantly decrease their total profits.

One of the solutions for BRPs to deal with imbalances lies in the battery energy storage (BES). The combination of variable resources and BES enables the generation company to control the quantity of electricity injected/withdrawn to/from the grid and thus adhere to the plan submitted to the TSO. Paper[14] proposed an investment model for BES installation in combination with an onshore UK wind farm. Paper [15] proposes a mathematical model for a wind power plant. Paper [16] investigates the compensation of the mismatch between forecasted PV power plant production and actual production by using three different forecasting models. Paper [17] considers investing in a solar power plant in combination with BES for an industrial plant. Authors of paper [18] proposed a model with BES as a price maker in the DA market, and a price maker in the reserve and activation market. Paper [19] investigates the impact of risk management in the management of BES. Paper [20] investigates how the integration of different renewables, energy storage, and demand response affects different power systems. All of these papers consider either the investment model of BES installation or investigate the impact of some other factors, such as risk management, on the BES management. Neither of these papers has proposed the operational model of a renewable energy resources (RES) plant coupled with BES and considered the imbalance settlement.

We have proposed a balancing model for renewable energy resources (RES) in cooperation with BES. The paper aims to investigate the potential of imbalance management for a production unit whose production depends on the weather forecast and therefore its output cannot be accurately predicted. Additionally, the potential of arbitrage in the DA market was investigated. The Section 2 presents the mathematical formulation, explains the objective function and constraints. It is followed by Section 3 where the case studies are presented. Cases with and without BES for prices from 2020 were elaborated in detail. Lastly, the Section 4 concludes the paper and highlights the findings.

2 Mathematical model

Objective function (1) aims at minimizing the deviation costs of the BRP. The first part of the equation refers to the penalization of the BRP in case of a deviation from the planned production, while the second part refers to the profit made by the day-ahead energy market positioning. In the case of negative $e^{\mathrm{d}}_{t,s}$, the system injects less energy than planned. Therefore, the objective function minimizes the penalties for deviation. On the other hand, in the case of positive $e^{\mathrm{d}}_{t,s}$ the system injects more energy than planned and in that case, the objective function maximizes the revenue realized by the deviation. The same principle was used in the second part of the objective function. When e^{mp}_t is negative it means that the facility purchases energy and therefore the objective function aims to minimize costs, while in the case of positive e^{mp}_t the facility sells energy to the grid and therefore the objective function maximizes the selling revenue. In other words, the purpose of the objective function is to maximize profit in both DA and imbalance markets by using historical deterministic prices.

$$\min \sum_{t}^{T} \Big(-\pi_s \cdot \sum_{s \in \Omega_s} (\lambda^{\mathrm{B}}_t \cdot e^{\mathrm{d}}_{t,s}) - \lambda^{\mathrm{DA}}_t \cdot e^{\mathrm{mp}}_t\Big) \tag{1}$$

Deviation of the BRP is defined as a difference between the realized production and the BRP market position given by eq. (2). The RES does not necessarily have to inject all production into the grid if this will cause its BRP deviation. Therefore, a new variable, $res^{\mathrm{r}}_{t,s}$, is introduced, which indicates how much of the total RES production is injected into the grid. The realized production of the BRP, given by eq. (3), depends on the RES's injected energy into the grid, trading in the DA market, and settlement at the imbalance mechanism. Market position of the BRP, given by eq. (4), depends on the RES's planned production and the planned trading in the DA market. The injected renewable energy is limited by its actual production, as given in eq. (5). Equations (6) – (7) refer to the grid exchange constraints. Equations (8) – (11) prevent simultaneous charging and discharging of the BES.

$$e^{\mathrm{d}}_{t,s} = e^{\mathrm{r}}_{t,s} - e^{\mathrm{mp}}_t, \quad \forall t, s \tag{2}$$

$$e^{\mathrm{r}}_{t,s} = (res^{\mathrm{r}}_{t,s} + dis^{\mathrm{DA}}_t - ch^{\mathrm{DA}}_t + dis^{\mathrm{B}}_{t,s} - ch^{\mathrm{B}}_{t,s}) \cdot \Delta t, \ \forall t, s \tag{3}$$

$$e^{\mathrm{mp}}_t = (RES^{\mathrm{pred}}_t + dis^{\mathrm{DA}}_t - ch^{\mathrm{DA}}_t) \cdot \Delta t, \quad \forall t \tag{4}$$

$$res^{\mathrm{r}}_{t,s} \le RES^{\mathrm{r}}_{t,s}, \quad \forall t,s \tag{5}$$

$$res^{\mathrm{r}}_{t,s} + dis^{\mathrm{DA}}_{t} - ch^{\mathrm{DA}}_{t} + dis^{\mathrm{B}}_{t,s} - ch^{\mathrm{B}}_{t,s} \le \overline{P^{\mathrm{ex}}}, \quad \forall t,s \tag{6}$$

$$RES^{\mathrm{pred}}_{t} + dis^{\mathrm{DA}}_{t} - ch^{\mathrm{DA}}_{t} \le \overline{P^{\mathrm{ex}}}, \quad \forall t \tag{7}$$

$$dis^{\mathrm{B}}_{t,s} \le (1-a) \cdot M, \quad \forall t,s \tag{8}$$

$$ch^{\mathrm{B}}_{t,s} \le a \cdot M, \quad \forall t,s \tag{9}$$

$$dis^{\mathrm{DA}}_{t} \le (1-b) \cdot M, \quad \forall t,s \tag{10}$$

$$ch^{\mathrm{DA}}_{t} \le b \cdot M, \quad \forall t,s \tag{11}$$

Equations (12) – (16) are BES constraints. The BES model is taken from [21] and adapted for the imbalance mechanism.

$$\begin{aligned} soe_{t,s} = {} & soe_{t-1,s} + \Delta t \cdot \eta \cdot (ch^{\mathrm{DA}}_{t} + ch^{\mathrm{B}}_{t,s}) - \\ & \Delta t \cdot \frac{1}{\eta} \cdot (dis^{\mathrm{DA}}_{t} + dis^{\mathrm{B}}_{t,s}), \quad \forall t,s \end{aligned} \tag{12}$$

$$soe_{t,s} \le soe^{\max} \tag{13}$$

$$soe_{t,s} = \sum_{j} soe^{\mathrm{p}}_{t,s,j}, \quad \forall t,s \tag{14}$$

$$soe^{\mathrm{p}}_{t,s,j} \le \sum_{i} (R_{i+1} - R_{i}) \cdot soe^{\max}, \quad \forall t,s,j \tag{15}$$

$$\begin{aligned} & \Delta t \cdot \eta \cdot (ch^{\mathrm{DA}}_{t} + ch^{\mathrm{B}}_{t,s}) \le F_{i=1} \cdot soe^{\max} - \\ & \sum_{i \ge 2} \sum_{j=i-1} soe^{\mathrm{p}}_{t-1,s,j} \cdot \frac{F_{i-1} - F_{i}}{R_{i} - R_{i-1}}, \quad \forall t > 1, s \end{aligned} \tag{16}$$

3 Case study

When determining the deviation and balancing costs, forecasted and realized solar power production values are needed. Since the actual production at the day-ahead level when submitting plans to the market operator and the TSO is unknown, scenarios and forecasts of actual production are introduced.

In the case study, the BES capacity is 5 MWh and the power rating is 5 MW, with the roundtrip efficiency 0.92.

3.1 Solar production

For solar production, we used PVSol [22] and Solcast [23] tools. PVSol tool was used to generate the forecast production curve. Using the Solcast tool, eight different realization scenarios were generated in the following way. First, the forecast and actual production curves were generated with a nominal power of 100 MW for a location in the southern part of Croatia. After that, errors between those two curves at each time period were calculated to obtain the error curve. To produce eight different scenarios, the error curve was shifted one day forward for each subsequent scenario, while the first day of the curve was shifted to the end of the curve. The obtained error curves were multiplied by the forecast curve generated by the PVSol tool, thus obtaining eight different scenarios for the realization of the solar power plant production. The obtained solar curves are given in Figure 1.

Tables 1 and 2 present a statistical analysis of each of the eight scenarios. The maximum and minimum values, the mean value, and the standard deviation of the positive and negative deviations were determined. The maximum values of the positive deviation range between 19,636 and 19.988 MW, while in the case of a negative deviation they range between 15.381 MW and 16.930 MW. The minimum deviation in all cases is exactly 0 MW. Based on this, it can be concluded that at certain time periods the production forecast is entirely accurate and the predicted values perfectly correspond to the realized values of a particular scenario. On the other hand, at certain moments a completely wrong estimate of production can occur. Mean values in both positive and negative deviations are around 3 MW. A uniform distribution is assumed for the occurrence probability of an individual scenario and therefore the occurrence probability of each scenario is set to $\pi_s = \frac{1}{8} = 0.125$.

Table 1 Statistical analysis of each solar production scenario – positive deviation

Scenario	**Max[MW]**	**Min[MW]**	**Mean**	**St. dev.**
1	19.931	0.000	3.352	3.418
2	19.712	0.000	3.138	3.176
3	19.841	0.000	3.159	3.203
4	19.988	0.000	3.177	3.236
5	19.924	0.000	3.168	3.217
6	19.906	0.000	3.101	3.191
7	19.982	0.000	3.138	3.170
8	19.636	0.000	3.143	3.177

Table 2 Statistical analysis of each solar production scenario – negative deviation

Scenario	**Max[MW]**	**Min[MW]**	**Mean**	**St. dev.**
1	15.480	0.000	3.312	3.309
2	15.594	0.000	3.277	3.277
3	15.381	0.000	3.299	3.304
4	16.930	0.000	3.315	3.315
5	15.485	0.000	3.221	3.217
6	15.971	0.000	3.234	3.228
7	15.487	0.000	3.280	3.273
8	16.790	0.000	3.256	3.259

3.2 Prices

Almost all aspects of human activity where affected by covid-19, and the electricity market is no exception. Therefore, we observed prices from 2020. Electricity prices in the DA market and imbalance prices during 2020 are provided in Figure 2.

3.3 Results

Segregated by months, the costs of the BRP are shown in Figure 3. Every month, the costs are negative, which means that the BRP is making a profit. Profit can be achieved when the realized production is higher than expected. Then $e^{\mathrm{r}}_{t,s}$ from eq. (2)

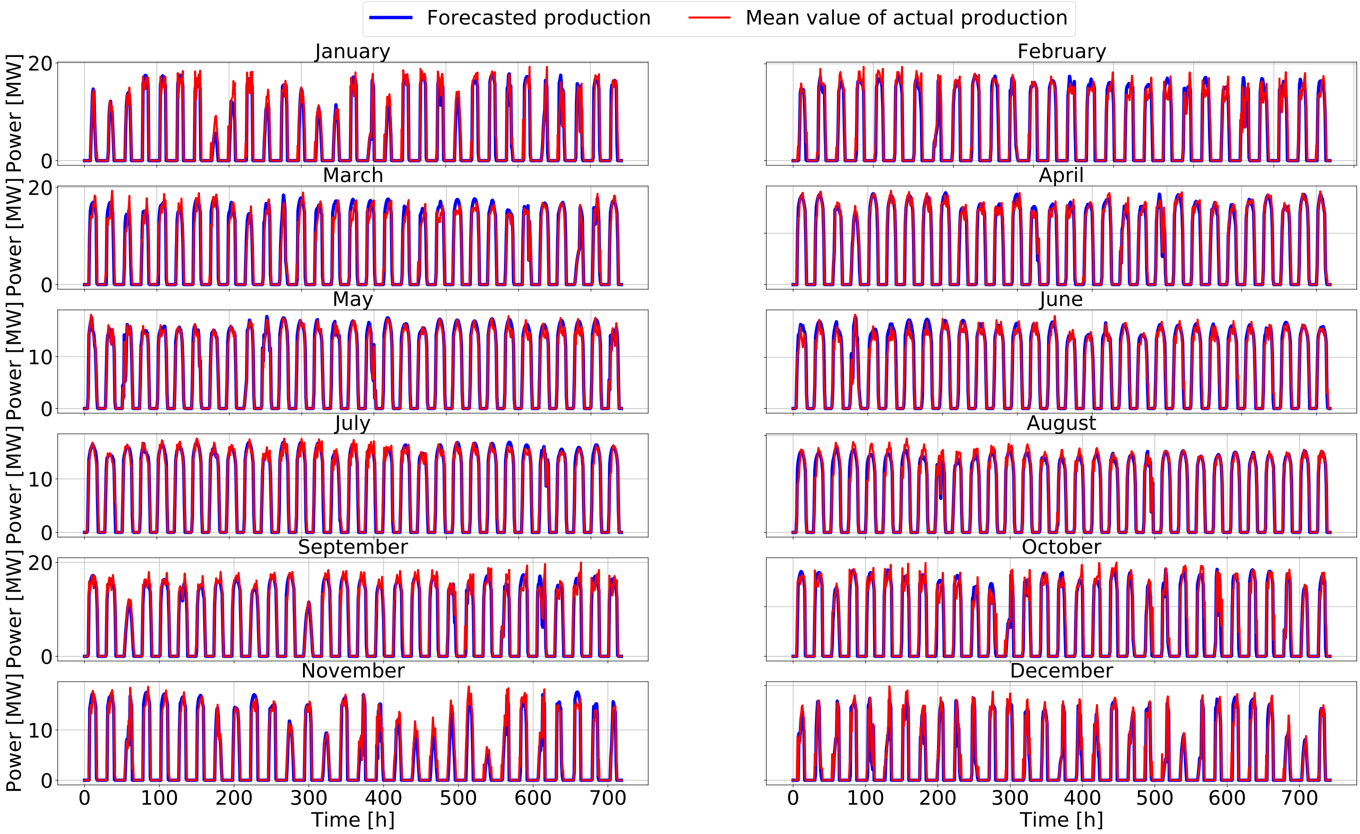

Fig. 1. Forecasted and actual solar production

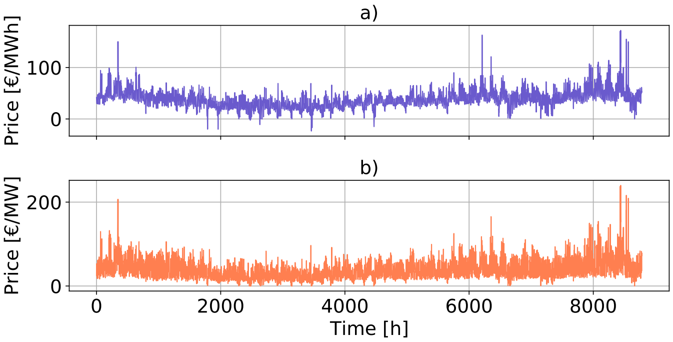

Fig. 2 a) Electricity prices in the DA market in 2020; b) imbalance prices in 2020

is greater than e_t^{mp}, so $e_{t,s}^{\mathrm{d}}$ may reduce the value of the objective function. On the other hand, e_t^{mp} can also affect the value of the objective function. Thus, what determines profit the most is the relationship between imbalance prices and prices in the DA market. Depending on the relationship between the prices, the BRP decides to reduce deviations or intentionally deviate in order to make an additional profit.

Table 3 shows segments of the profit in case without a BES. Without the BES, a profit of 2 171 244 € was realized. The vast majority of profit, i.e. 2 068 829 €, comes from trading, while the profit due to deviations is around 102 415 €.

An increase in profit is possible by the installation of BES. The profit, with the 5 MWh/ 5 MW BES, is € 2 371 531, which is an increase of 9.22% compared to the case without the BES. Trading profit has increased by 0.44%, while deviation profit has increased by 102.67%, as shown in table 4. The BES enables the BRP to increase profit from trading as well as from deviations by making an arbitrage. Since the prices during the solar production are favorable, i.e. it is profitable to sell energy, the system is not motivated to store energy in order to sell it later. Therefore, the system prefers to use the BES capacity to reduce deviations. Every month, as shown in Figure 3, the BRP is more profitable with BES rather than without the BES.

Figures 4 and 5 show the realized production and market position in the case of with and without the BES during one day in July and December, as well as BES's charging, discharging, and the state of energy. The main goal of the optimization model is to maximize profit from electricity trading by reducing deviation costs by optimum battery management. Due to market conditions, it is evident that deviations in the case with the BES are larger and more frequent than in the case without the BES, but the profit in these cases is also higher.

Table 3 System profit by segment without the BES

Deviation profit [€]	102 415
Trading profit [€]	2 068 829
Profit [€]	2 171 244

Table 4 System profit by segment with the BES

Deviation profit [€]	293 596
Trading profit [€]	2 077 935
Profit [€]	2 371 531

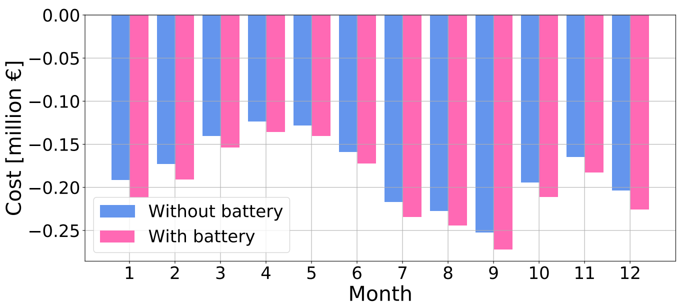

Fig. 3. Monthly costs without and with the BES

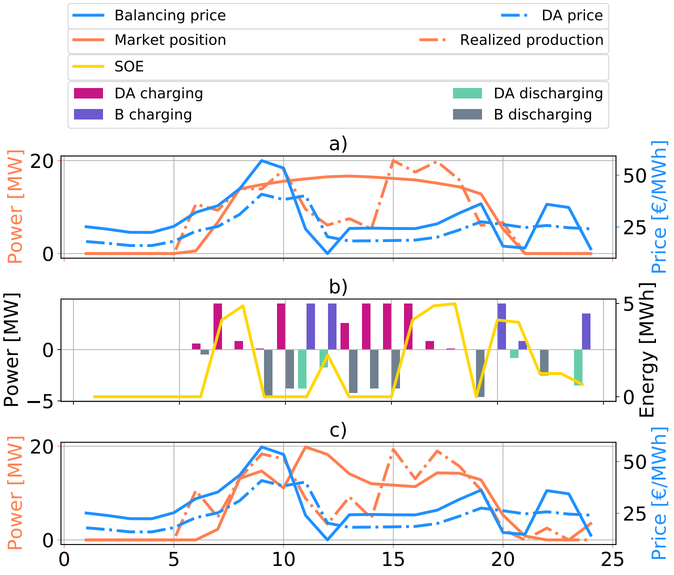

Fig. 4 Random day in July: a) Market position and realized production without BES; b) Charging and discharging of the BES; c) Market position and realized production with BES

In cases where the system's behavior with an installed BES is shown, it is evident that the BRP intentionally makes positive deviations when the imbalance price is higher than the price on the DA market. On the other hand, when the imbalance price is lower than the DA market price, the BRP intentionally makes negative deviations. This is enabled by the BES large enough to store or deliver the required energy as needed.

For example, on a random day in December, shown in Figure 5, at hour 10, the imbalance price is much lower than the price in the DA market. In the case without the BES, there is no deviation between market position and realized production in order for BRP not to get sanctioned. On the other hand,the BES enables the BRP at that same hour to make a negative deviation by charging BES and discharging at the DA market. In this way, BRP achieves additional profit compared to the case without the BES.

The opposite is happening in the next period, starting from hour 12. The imbalance price in this case is much higher than the price in the DA market. Therefore, in the case of with the BES, the BRP is making positive deviations by BES discharging and DA charging.

On a arbitrary day in July, shown in Figure 4, the BES is performing three and a half cycles of charging and discharging, enabling the BRP to manage the deviations even better and consequently making even more additional profit.

It is important to note that the optimization model knows the deviation prices in advance, which is not the case in reality.

4 Conclusion

An operational model that considers the balancing stage for a RES in cooperation with a BES is proposed. To test the proposed model, forecasted and actual production curves were derived. With BES, for prices from 2020, profit has an increase of 9.22% compared to the case without the BES. BES enables not only better imbalance management, but also additional profit by arbitrage in the DA market.

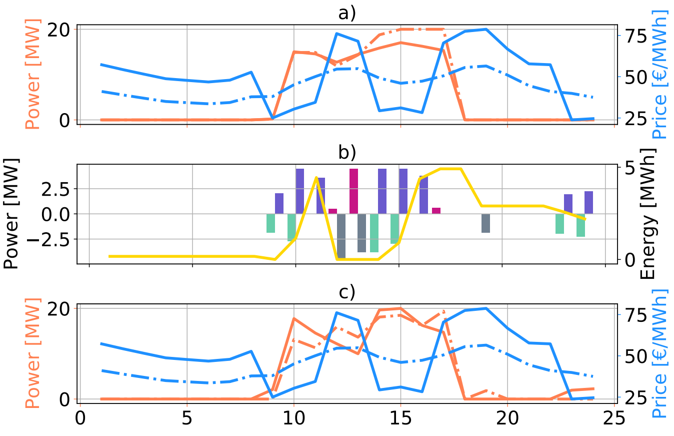

Fig. 5 Random day in December: a) Market position and realized production without BES; b) Charging and discharging of the BES; c) Market position and realized production with BES

Despite many benefits that BES brings in combination with RES, it is still an expensive technology. Therefore, it is necessary to investigate the investment costs and the rate of return on investment as well as the appropriate size of the BES. The investment and sizing part of the model is a line left for future work.

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