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► **To cite this version:**

Ahmed Mohamed, Rémy Rigo-Mariani, Vincent Debusschere, Lionel Pin. Management Strategies for BESS Storage Systems Participating in Joint Energy and Reserve Markets. 2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Oct 2024, Dubrovnik, Croatia. pp.1-5, <10.1109/ISGTEUROPE62998.2024.10863131>. <hal-05098045>

HAL Id: hal-05098045

<https://hal.science/hal-05098045v1>

Submitted on 4 Jun 2025

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Management Strategies for BESS Storage Systems Participating in Joint Energy and Reserve Markets

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Abstract— BESS Energy Storage Systems (BESS) are increasingly recognized as crucial participants in the energy market, offering versatile grid services. To maximize profitability, this paper explores the opportunity to stack services while participating in the Day-Ahead market (DA) and the Frequency Containment Reserve (FCR) market. Look-ahead optimization is proposed assuming that energy and reserve prices and requirements are known to examine the interplay between DA and FCR products. In particular, two management strategies are proposed to provide the two services and hence evaluate the maximum theoretical profits assuming a perfect price forecast. Strategy (a) allows participation in only one service at each hour of the day. Strategy (b) enables the simultaneous provision of the two services all the time. Additionally, a baseline case is introduced while allowing the BESS to participate only in one market. The simulations use historical data to compute the DA energy and FCR schedule. Furthermore, a storage degradation analysis is performed to evaluate the effect of the predicted operations on the BESS lifetime, considering both cycling and calendar aging.

Index Terms— Energy markets, BESS degradation, Frequency Reserve, Optimization, Stacked revenues.

I. INTRODUCTION AND STATE-OF-ART

In recent years, Europe has seen an exceptional surge in renewable energy integration in the power grid driven by the objectives of the European Union to reduce CO₂ emissions [1]. The renewable source's intermittent nature causes unpredictable power fluctuations. As a result, there has been a notable increase in the deployment of Battery Energy Storage Systems (BESS) in order to provide flexibility to the grid [2]. BESSs then help to ensure grid stability and reliability by providing ancillary services to the transmission system operator (TSO). Despite the vital role of the batteries, the high costs of the investment and the management hinder the expansion of the projects. This economic viability of BESS projects can be enhanced by leveraging the BESS participation in different services to maximize revenues [3].

Due to the flexibility in the storage sizing, the operation horizon can align with the trading resolutions of these markets. The optimal energy arbitrage typically consists of buying energy during off-peak hours at a lower price and selling it during peak hours at a higher price. Higher revenues can be expected with BESS able to generate high revenues by participating in both Day-Ahead (DA) and Intraday (ID) energy markets [4]. Moreover, BESS has the characteristic of rapid response capability which enables it to instantaneously inject or absorb power in response to fluctuations in frequency [5]. This

inherent agility positions BESS as an ideal candidate for applications like Frequency containment reserve (FCR), where immediate regulation action is essential to prevent frequency excursions [5].

BESS has demonstrated its capability to engage in multiple services owing to its high energy density, rapid response time, and scalability to the grid level [6]. Several studies, including [7], and [8], have implemented Mixed Integer Linear Programming (MILP) to assess the BESS profitability in different markets. In particular, [9] investigates the potential of BESS participating in energy arbitrage in the PJM market, while [7] focuses on the evaluation of BESS for frequency services in the CAISO market. Providing a stack of services of both energy arbitrage and frequency regulation has been also proposed in [10] in the USA market. Furthermore, the BESS owner can prioritize some of the services, such as outage mitigation for grid security [10]. The authors in [11] have shown that frequency regulation overperformed the other services while investigating stacking revenues in European markets.

Most of the studies as mentioned earlier have assessed the economic feasibility of BESS participating in various energy markets. However, the majority have followed the regulations of the USA markets [9], Nordic markets [12], and German national markets using pay as bid market structure [13]. Furthermore, there is not much recent work that presents the markets with the updated European regulations [14], especially the new bidding rules for frequency services and reserve activation. Except in [11] where European regulations were considered, however, an assumption was made for the FCR energy activation, and real-time frequency deviations were not followed. These optimal service portfolios have been developed to maximize the expected revenues of BESS. However, they do not extensively address the effects on the BESS lifetime. In this paper, the FCR is modeled accurately with automatic activation of a 1 min resolution. Moreover, the study proposes two different management strategies to stack DA and FCR markets while considering BESS degradation. The BESS is considered a price taker, where the bids/offers are always accepted. The main contributions of this paper can be summarized as follows:

- Modeling the BESS operation in DA and FCR markets.
- Proposing two management strategies for stacking revenues with annual simulations for economic valuation.
- Analysis of BESS degradation while stacking the services.

The rest of the paper is organized as follows. Section II presents the markets and mathematical modeling for the BESS

and the degradation model. Section III proposes two optimization strategies for stacking revenues in DA and FCR markets. Section IV shows the results of the annual simulations and analysis for the BESS lifetime. Section V concludes the paper and discusses the ongoing investigations.

II. MARKETS DESCRIPTION AND MODELING OF THE BESS

A. Day Ahead market (DA)

DA enables the market actors to buy and sell energy markets in daily auctions with a horizon of 24 hours and at a resolution of one hour in France [15]. The energy trade is done in power exchange markets, where the energy products are standardized bids (by buyers) and offers (by sellers). The remuneration of these energy products is based on quantity (in €/MWh).

B. Frequency Containment Reserve in Europe

In Europe, the FCR reserve is a 4h duration product that is available in both directions (symmetric reserve). The BESS owner gets remunerated for the reserve in €/MW. The activation of the reserve is automatic and proportional to the frequency deviations (Δf) in 1min resolution. The FCR-activated power is determined as a ratio of the procured reserve, where 100% of the reserve is activated if the maximum deviation is reached ($\Delta f_{\max} = 200$ mHz) [16]. There is a remuneration for the FCR-activated energy in €/MWh [17]. BESSs are allowed to participate in the FCR under the rule of “15 min criterion”, which imposes the availability of the procured symmetric reserve for at least 15 min [18].

C. BESS Model

The operation model for the BESS is based on the optimal bidding over DA and FCR markets. The markets' equations are to be considered as constraints in the MILP optimization. The operating model accounts for the energy storage capacity (E_{cap}), the maximum power charging/discharging rate (P_{max}), charging and discharging efficiencies (η , η^+), and BESS state of charge's limits (soc_{min} , soc_{max}). Typical constraints (1) and (2) limit the charging and discharging power flows at any time step (p_t^+ , p_t^-) by the BESS power capacity. The stored energy is updated at each time step accounting for charging and discharging efficiencies in (3). and shall remain between predefined maximum and minimum soc levels (4). The BESS power will be the aggregated participation over the DA and FCR markets.

$$0 \leq p_t^+ \leq p_{max} \quad (1)$$

$$0 \leq p_t^- \leq p_{max} \quad (2)$$

$$soc_t = soc_{t-1} + (p_t^- \times \eta^- - p_t^+ / \eta^+) \times dt \times (100 / E_{cap}) \quad (3)$$

$$soc_{min} \leq soc_t \leq soc_{max} \quad (4)$$

D. Degradation Model for BESS

The proposed optimization strategies will affect the BESS operation and hence they will have an impact on its degradation over time. Even if BESS aging is not at the core of the proposed paper, a degradation model developed by [19] is used to evaluate the capacity fade incurred by the BESS usage simulated. The authors have developed and parametrized the models using LiFePO4/C BESS cells at 25 °c to measure both cycling and calendar aging. The calendar aging represents the

capacity loss ($c^{loss, cal}$) as a function of the idling soc level (soc^l) and the time in months (t), as shown in (5). The cycling aging represents the capacity loss due to the soc variation either charging or discharging. The cycling capacity loss ($c^{loss, cyc}$) is a function of the depth of discharge (dod), the number of cycles that occurred at this dod (n), and the average soc during these cycles (soc^{av}), as presented in (6). The degradation model embeds a rain flow algorithm that is developed and applied to the annual soc profile of each controller, to count the number of cycles at each distinct depth of discharge and also compute the average soc during these cycles.

$$c^{loss, cal} = 0.1723 \times e^{0.0073 \times soc^l} \times t^{0.8} \quad (5)$$

$$c^{loss, cyc} = 0.021 \times e^{-0.0194 \times soc^{av}} \times dod^{0.716} \times n^{0.5} \quad (6)$$

III. FORMULATION OF THE OPTIMIZATION STRATEGIES

In this section, we investigate the provision of both energy arbitrage and frequency services using a single BESS to better utilize both reserve (MW) and energy (MWh). The proposed look-ahead optimization frameworks examine the interplay between DA and FCR products, as shown in Fig. 1. Two management strategies are proposed. Strategy (a) allows participation in only one service at each hour of the day. Strategy (b) simultaneously provides the two services all the time. The baseline case is considered by allowing the BESS to participate in only one market.

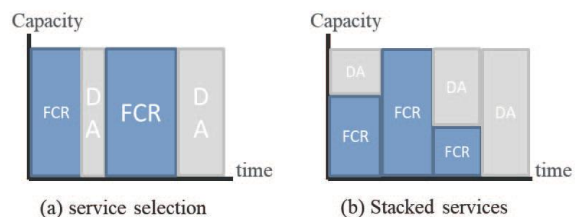


Fig. 1 Management Strategies for Stacked Revenues in DA and FCR

A. Strategy (a): Service selection

The BESS operation in the DA market consists of charging or discharging power. The BESS operator chooses either to charge or discharge based on the energy prices and the BESS soc. On the other hand, while providing FCR, the BESS changes status between charging and discharging every minute based on the frequency deviations measured. Thus, in this strategy, only one service is provided at a time. At the beginning of each hour, the BESS selects to participate either in DA for the next hour or to allocate FCR reserve and follow the activation directionals for the next four hours. In such a case, the control is relatively straightforward because there is no risk of charging and discharging at the same time across the different markets.

The objective function (7) maximizes the profits from the joint DA and FCR markets following strategy (a). The DA discharge and charge energy products $p_{t^{da}}^{da+}$, $p_{t^{da}}^{da-}$ are optimized over a 1h resolution over the time set $t^{da} \in T^{da}$. The constraints (8) and (9) set the energy products limits with respect to the BESS power capacity. The binary variables $u_{t^{da}}^+$, $u_{t^{da}}^-$ assure that only charging or discharging BESS status is selected, as shown in constraint (10). The FCR reserve $p_{t^{cr}}^{cr}$, is allocated over 4h resolution over the time set $t^{cr} \in T^{cr}$. The constraint (11) limits the FCR reserve to the BESS capacity and allows the

FCR participation when there is no DA products committed. The 15 min criterion rule for the FCR reserve is introduced in (12). The FCR activation $\Delta p_{t^a}^{fcr+}$, $\Delta p_{t^a}^{fcr-}$ is linear with the frequency measurements and updated on 1 min resolution over the time set $t^a \in T^a$, as shown in (13). The total charging and discharging powers of the BESS at each time step are calculated in (14) and (15). These powers are then used to update the BESS soc at every time step.

$$\max_{p_{t^a}^{da-}, p_{t^a}^{da+}, p_{t^a}^{fcr}} \sum_{t^a \in T^{da}} \pi_{t^a}^{da} \times (p_{t^a}^{da+} - p_{t^a}^{da-}) \times dt^{da} + \quad (7)$$

$$\sum_{t^r \in T^r} \sum_{t^a \in T^a} \pi_{t^r}^{fcr} \times p_{t^r}^{fcr} + \pi_{t^r}^{fcr} \times dt^a \times (\Delta p_{t^a}^{fcr+} - \Delta p_{t^a}^{fcr-})$$

$$p_{t^a}^{da+} \leq p_{\max} \times u_{t^a}^+ \quad (8)$$

$$p_{t^a}^{da-} \leq p_{\max} \times u_{t^a}^- \quad (9)$$

$$u_{t^a}^+ + u_{t^a}^- \leq 1 \quad (10)$$

$$p_{t^r}^{fcr} \leq p_{\max} \times (1 - u_{t^r}^-) \times (1 - u_{t^r}^+) \quad (11)$$

$$E_{cap} / p_{t^r}^{fcr} \geq 0.5h \quad (12)$$

$$\Delta p_{t^a}^{fcr+/-} = \begin{cases} p_{t^a}^{fcr}, & \text{if } |\Delta f_{t^a}| \geq |\Delta f_{\max}| \\ (|\Delta f_{t^a}| / |\Delta f_{\max}|) \times p_{t^a}^{fcr}, & \text{if } |\Delta f_{t^a}| \leq |\Delta f_{\max}| \\ 0, & \text{if } |\Delta f_{t^a}| \leq |\Delta f_{\max}| \end{cases} \quad (13)$$

$$p_t^+ = p_{t^a}^{da+} + \Delta p_{t^a}^{fcr+} \quad (14)$$

$$p_t^- = p_{t^a}^{da-} + \Delta p_{t^a}^{fcr-} \quad (15)$$

B. Strategy (b): Services Stacking

In Strategy (b), the BESS is allowed to participate in both markets (DA and FCR) at every time step along the day-ahead horizon. The previous conventional formulations for frequency containment reserve (FCR) have been dependent on the BESS charging/discharging state. This means that upward reserve can only be supplied while discharging and downward reserve can only be provided while charging, which are donated as direct reserves. To adapt the BESS operation to the change of status between charging and discharging due to FCR activation, the proposed model is based on four modes of operations to provide reserve: charging less, charging more, discharging less, and discharging more. In the charging state, the downward reserve can be provided by increasing the charging power, while the upward reserve can be provided by charging less. Similarly, in discharging mode, the downward reserve can be provided by discharging less, and an upward reserve can be provided by discharging more. The different operation modes are illustrated in Fig. 2. By utilizing this reserve formulation, the capacity of BESS FCR reserve increases by utilizing the committed discharge energy as a downward reserve, and the committed charge energy as an upward reserve, which are donated as opposite reserves.

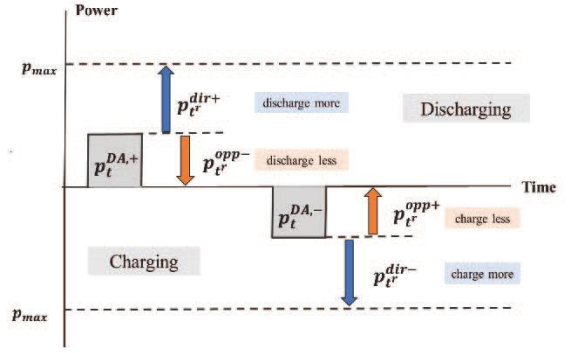


Fig. 2 Different operation modes for stacking DA and FCR products [17]

A similar approaches were proposed in [17,24] with assumption for the FCR activation and without considering the new 4h reserve regulations, respectively. In this work, the symmetric reserve with 4h resolution is considered and the activated energy is linear with frequency deviations. Two continuous variables ($p_{t^r}^{dir}$, $p_{t^r}^{opp}$) are introduced for the FCR reserve, as shown in the objective function (16). Specifically, $p_{t^r}^{dir}$ represents the direct FCR reserve for regulation in the same direction as the committed energy in the DA market, and $p_{t^r}^{opp}$ represents the FCR reserve for regulation in the opposite direction. In addition, the variables $\Delta p_{t^a}^{dir+}$, $\Delta p_{t^a}^{dir-}$, $\Delta p_{t^a}^{opp+}$, $\Delta p_{t^a}^{opp-}$ represent the FCR activation quantities. The traditional constraints for the operation of joint energy and reserve problem are presented in (17) - (20). Constraints (17) and (18) limit the total BESS output at charging and discharging modes. They represent the operations of discharging more to supply upward regulation and charging more to supply downward regulation respectively, as shown in blue arrows in Fig. 2. Since FCR is a symmetric reserve product that follows the 15 min criterion rule, the minimum value from both up and down reserves ($p_{t^r}^{dir+}$, $p_{t^r}^{dir-}$) is selected, which is constrained by (19) and (12). The binary variables ($u_{t^a}^+$, $u_{t^a}^-$) are introduced to avoid charging and discharging at the same time in (20).

$$\max_{p_{t^a}^{da-}, p_{t^a}^{da+}, p_{t^r}^{dir}, p_{t^r}^{opp}} \sum_{t^a \in T^{da}} \pi_{t^a}^{da} \times (p_{t^a}^{da+} - p_{t^a}^{da-}) \times dt^{da} + \sum_{t^r \in T^r} \sum_{t^a \in T^a} \pi_{t^r}^{fcr} \times (p_{t^r}^{dir} + p_{t^r}^{opp}) \quad (16)$$

$$+ \pi_{t^r}^{fcr} \times dt^a \times (\Delta p_{t^a}^{dir+} + \Delta p_{t^a}^{opp+} - \Delta p_{t^a}^{dir-} - \Delta p_{t^a}^{opp-})$$

$$p_{t^r}^{dir+} + p_{t^a}^{da+} \leq p_{\max} \times u_{t^a}^+ \quad (17)$$

$$p_{t^r}^{dir-} + p_{t^a}^{da-} \leq p_{\max} \times u_{t^a}^- \quad (18)$$

$$p_{t^r}^{dir} = \min(p_{t^r}^{dir+}, p_{t^r}^{dir-}) \quad (19)$$

$$u_{t^a}^+ + u_{t^a}^- \leq 1 \quad (20)$$

Constraints (21) and (22) introduce the new reserves that allow FCR regulation in the opposite direction of the committed energy in DA. Where (21) allocates the discharge energy product of DA as a downward FCR reserve, and (22) allocates the charge energy product of DA as an upward FCR reserve. That is illustrated in orange arrows in Fig. 2. The constraints (21) and (22) are non-linear, due to the multiplication of the binary variables with the continuous variables. Linearized constraints are then introduced in (27) - (30) to replace them,

using the Big M method [21], where the continuous variables ($z_{t,r}^{opp+}$, $z_{t,r}^{opp-}$) and the binary variables ($u_{t,r}^{opp+}$, $z_{t,r}^{opp-}$) were introduced. Constraint (23) defines the four modes slots by allowing to provide FCR regulation in the opposite direction of DA energy products. Equations (25) and (26) define the total discharged and charged energy at each time step to be used for the soc calculations.

$$p_{t,r}^{da+} - p_{t,r}^{opp-} \times u_{t,r}^{opp-} \geq 0 \quad (21)$$

$$p_{t,r}^{da-} - p_{t,r}^{opp+} \times u_{t,r}^{opp+} \geq 0 \quad (22)$$

$$u_{t,r}^{opp+/-} \leq u_{t,r}^{+/-} \quad (23)$$

$$p_{t,r}^{opp} = \min(p_{t,r}^{opp+}, p_{t,r}^{opp-}) \quad (24)$$

$$p_{t,r}^+ = p_{t,r}^{da+} + \Delta p_{t,r}^{dir+} - \Delta p_{t,r}^{opp-} \quad (25)$$

$$p_{t,r}^- = p_{t,r}^{da-} + \Delta p_{t,r}^{dir-} - \Delta p_{t,r}^{opp+} \quad (26)$$

$$p_{t,r}^{da+} - z_{t,r}^{opp+} \geq 0 \quad (27)$$

$$z_{t,r}^{opp+} \geq p_{t,r}^{opp} - (1 - u_{t,r}^{opp+}) \times p_{\max} \quad (28)$$

$$p_{t,r}^{da-} - z_{t,r}^{opp-} \geq 0 \quad (29)$$

$$z_{t,r}^{opp-} \geq p_{t,r}^{opp} - (1 - u_{t,r}^{opp-}) \times p_{\max} \quad (30)$$

IV. SIMULATIONS AND OBTAINED RESULTS

Energy, reserve prices, activation prices, and frequency deviations were collected from the French TSO (Rte) and Entso-e 2021 databases [22]. A 10 MW/10 MWh BESS is considered with the following parameters: $\eta = \eta^+ = 0.9$, $\text{soc}_0 = 50\%$, soc limits of $\text{soc}_{\min} = 25\%$, and $\text{soc}_{\max} = 75\%$ due to the 15 min criterion rule. The annual results for the baseline showed that participating in the DA market could achieve 180 K€, and participating in the FCR market could achieve 818 K€ with 11.8 GW reserve over the year.

A. Annual simulations

The management strategy with stacked services, strategy (b), achieved the highest expected revenue of 1,431,941 € over the simulated year with an increase of 49 % compared to the baseline and 15 % compared to strategy (a). Fig. 3 shows the huge increase in profits while providing joint energy and reserve markets. The results show that the two strategies achieved more profits than using two BESSs each participating in a single market DA and FCR. It can be noted that while using the service selection strategy, DA was mostly used to charge the BESS as a result there were not many profits generated from energy arbitrage in that case. However, while stacking the markets, the BESS could benefit from both markets resulting in higher revenues.

For strategy (a), the BESS mainly uses the DA energy products to charge and be able to provide more FCR reserve. In the cases where no FCR is provided, energy arbitrage is used to generate additional revenues. This can be seen at 4h:00 and 17h:00 in Fig. 4 which illustrates daily operations. The allocated reserve on that day has increased by 42 % compared to the baseline. The four modes of operation in strategy (b)

allow the BESS to increase its reserve capacity. The analysis revealed that the FCR reserve increased by around 100 %, compared to the baseline over the same day. That resulted in doubling the daily revenues from the FCR market. This outcome is explained by the ability of the BESS to utilize the energy committed in the DA market as a reserve and to provide both upward and downward regulation at any time. For example, between 00h:00 and 04h:00, FCR reserve could be allocated due to the use of DA products as reserves, as shown in Fig. 4. That was not the case for Strategy (a), where no FCR reserve was allocated and only DA was used. On the other hand, the reserve was reduced between 04h:00 and 08h:00, to allow charging from the DA market. That allowed allocating more FCR reserves for the rest of the day. This strategy increased the annual FCR reserve up to 19.8 GW compared to 17.2 GW in strategy (a).

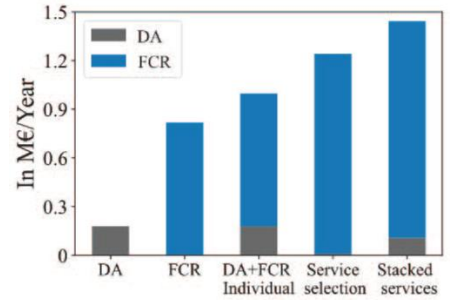


Fig. 3 Annual simulations for different management strategies

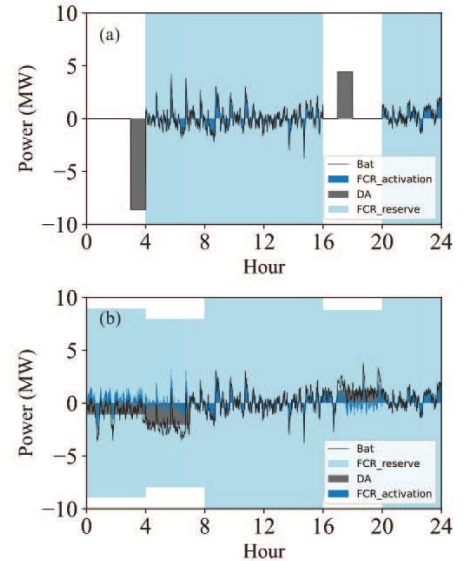


Fig. 4 Daily simulation results in a) Strategy (a) – b) Strategy (b)

B. BESS lifetime analysis

Switching from one service to the other in strategy (a) results in rapid changes in the soc level of the BESS as shown in Fig. 5. This is due to the energy arbitrage of the DA market, where the BESS charges or discharges with high quantities to achieve profits. This high depth of discharge (DoD) impacts the BESS degradation and hence the project lifetime. However, for strategy (b), the increase in reserve did not have a negative effect on the BESS soc profile. The simulation results in Fig. 5 show the gradual increase/decrease in the BESS soc level with small DoD whenever frequency regulation occurs. This is due

to the continuous energy activation of the FCR reserve, where the DA energy output adapts every minute to the frequency deviations.

The annual soc profile was decomposed into idling and cycling profiles to calculate the capacity fade due to calendar and cycling aging. Since the simulation was only for one year, the posterior degradation analysis was performed by feeding the same soc profile successively to measure the accumulated behavior over 10 years using the correction factors presented in [19]. The results in Fig. 6 show that strategy (b) incurs less degradation. This is due to the high values of DoD caused by strategy (a) which in turn increases the cycling aging and reduces the BESS lifetime.

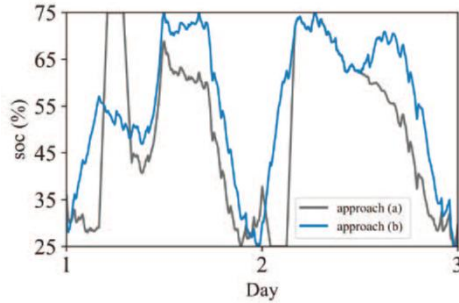


Fig. 5 Soc profile for three days using different optimization strategies

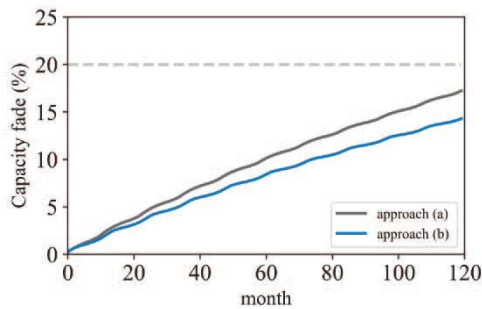


Fig. 6 Degradation analysis for the optimization strategies over 10 years.

V. CONCLUSIONS

The paper proposed two optimization strategies to provide joint energy and reserve products using a single BESS. The findings highlight that strategy (b), which involves simultaneously stacking both DA and FCR products, yields the highest profits, amounting to 1.4 million euros. This represents a substantial 76 % increase in profits compared to providing only FCR (baseline). Strategy (a), which allows the BESS to select between the two services, also outperformed the baseline but only with an increase of 48%. Moreover, strategy (a) leads to an increase in the DoD of the BESS soc profile while switching from one service to another. That leads to an increase in the cycling aging of the BESS and hence reduces the lifetime. Over 10 years, Strategy (a) resulted in a capacity fade of 17%, compared to 14% for Strategy (b). The study provides valuable insights for BESS operators to maximize their profitability from DA and FCR markets. Stacking services (strategy b) have proven to be more profitable with less damage to the BESS degradation compared to participating in a single market (baseline) or switching between two markets (strategy a). Future work includes optimal sizing for BESS in different markets while considering more accurate storage modeling and part load efficiency.

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