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Ahmed Mohamed, Rémy Rigo-Mariani, Vincent Debusschere, Lionel Pin. Optimal Sizing and Economic Valuation of an Energy Storage System Participating in Joint Energy and Reserve Markets. IEEE PES Innovative Smart Grid Technologies Conference (ISGT–Europe 2024), Oct 2024, Dubrovnik, Croatia. <10.1109/ISGTEUROPE62998.2024.10863798>. <hal-04938998>

**HAL Id: hal-04938998**

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Submitted on 4 Jun 2025

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# Optimal Sizing and Economic Valuation of an Energy Storage System Participating in Joint Energy and Reserve Markets

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**Abstract** - This paper evaluates the participation of a grid-connected BESS Energy Storage System (BESS), in the Day ahead (DA) and Frequency Containment Reserve (FCR) markets in Europe. Through annual simulations, the study demonstrates the substantial revenue potential of providing multiple services (DA+FCR) by a single BESS, resulting in a significant 74% increase compared to the sum of individual markets' participation. Furthermore, a comprehensive sensitivity analysis is conducted to determine the optimal sizing of the BESS, revealing the advantages of higher power-to-energy ratios in terms of profitability and payback periods. An oscillation penalty is introduced to mitigate the BESS degradation by reducing the BESS's depth of discharge. This leads to a reduction of BESS capacity fade behavior by 7 % while incurring only a marginal 9 % loss in the annual revenues. These findings contribute valuable insights for decision-making in deploying grid-connected batteries, considering revenue optimization and BESS performances.

**Keywords**—Energy Markets, Energy Storage, Optimal sizing, Economic analysis, BESS degradation.

## I. INTRODUCTION

The growing adoption of Renewable Energy Sources (RES) in the electricity generation mix requires increased flexibility in the power system resources. Indeed, the intermittent nature of RES leads to greater reserve requirements in to mitigate the unpredictability of power fluctuations. The integration of Energy storage systems (ESSs) into the electrical grid infrastructure has long been investigated to provide such reserve, which in turn allows for greater penetration of RES [1]. At the same time, BESS Energy Storage Systems (BESS) costs are decreasing due to intensive research and development in chemistry and power conversion systems.

ESS have the potential to provide various services such as frequency regulation, peak shaving, voltage control, transmission and distribution investment deferral, and energy arbitrage [2]. Hence, there has been a surge in the number of entities that may implement and operate ESSs, particularly transmission or distribution operators to maintain grid stability, energy suppliers to minimize losses and maximize profits, and consumers who seek to lower their energy expenses or earn additional revenues through their active participation in the energy markets [3].

Extensive research has been carried out to demonstrate the suitable services for each type of energy storage technology, among which BESS is the most promising type, capable of participating in multiple services due to its high energy density, fast response time, and potential to scale up to grid level [4]. Several studies, including [5], and [6], have implemented Mixed Integer Linear Programming (MILP) to assess the BESS profitability by its participation in different energy markets. In

particular, [7] investigates the potential of BESS participating in Energy arbitrage in the PJM market, while [8] focuses on the evaluation of BESS for frequency services in the CAISO market. Providing a stack of services of both energy arbitrage has been also proposed in [9] in the USA market. Moreover, the BESS is used for providing distribution services such as peak shaving and self-consumption [10]. The authors in [11] introduce a framework for energy storage and demand response optimization from the demand response aggregator's perspective.

Most of the aforementioned studies have proposed control strategies for BESS that enable participation in multiple services. These schemes aim to assess the technical feasibility of BESS participating in various energy markets while ensuring that their profitability is not compromised for any individual service. Most of the studies have followed the regulations of the USA markets [7], Nordic markets [12], and German markets using pay as bid market structure [13]. There is no much recent work that presents the markets with new European regulations [14], especially the new bidding rules for frequency services. These optimal service portfolios have been developed to maximize the expected revenues of BESS. However, their primary focus was on evaluating the stacked services and do not extensively address the effect of BESS sizing on the stack performances. Moreover, the impact of sizing on the profitability of BESS investment in terms of payback period.

In the present discourse, this work accurately models the various markets in which BESSs can generate revenue by actively participating in them. Deterministic optimization is introduced based on recent historical data to evaluate the revenues of joint energy and reserve markets. Furthermore, it aims to conduct a sensitivity analysis to determine the optimal size of a BESS that can profitably participate in DA and FCR markets. An economical valuation is presented based on the Net Present Value (*NPV*) metric to estimate the payback period of such investment. The present research endeavors to expand the scope of the analysis by incorporating an oscillation penalty factor that mitigates BESS degradation. The paper's main contributions are:

- The modeling of jointed energy (DA) and reserve (FCR) markets within the European framework.
- The introduction of an oscillation penalty for the BESS operation to reduce aging.
- Optimal sizing for the energy-to-power ratio to the BESS based on the total cost of ownership.

The rest of the paper is organized as follows. Section II describes the models considered for the BESS participating in energy and reserve markets modeling in Europe. Section III introduces the case study with simulations and results.

Section IV concludes with an assessment of the models and proposes perspectives for future work.

## II. BESS IN ENERGY AND RESERVE MARKET

### A. Energy storage model for the MILP optimization

The BESS model accounts for the energy storage capacity ( $E_{cap}$ ), the maximum power charging/discharging rate ( $P_{max}$ ), charging and discharging efficiencies ( $\eta^-$ ,  $\eta^+$ ), BESS state of charge's limits ( $soc_{min}$ ,  $soc_{max}$ ). The BESS model is generic, where the power values are decided based on the summation of the selected markets.

$$0 \leq p_t^+ \leq P_{max} \times u_t \quad (1)$$

$$0 \leq p_t^- \leq P_{max} \times (1 - u_t) \quad (2)$$

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

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

Constraints (1) and (2) limit the charging and discharging power flows ( $p_t^+$ ,  $p_t^-$ ) by the BESS power capacity. A binary variable  $u_t$  is introduced to avoid potential simultaneous charging and discharging. Here the binary variable denotes the charging mode of the storage. Note that a typical alternative could have consisted in introducing two distinct variables for charging and discharging modes. It has not been considered here for a reduced problem complexity. The stored energy is updated at each time step accounting for charging and discharging efficiencies in (3). This stored energy is limited by (4) between predefined maximum and minimum state of charge ( $soc$ ) levels.

### B. Day-ahead market (DA)

This market aims at providing an initial operating schedule for the TSO to meet the daily predicted demand. It has a horizon of 24 hours and a resolution of one hour in all European countries except in the United Kingdom, where the resolution is 30 min [15]. BESS can participate in DA by providing hourly bids for energy products - either by charging ( $p_t^{da-}$ ) or discharging ( $p_t^{da+}$ ). The remuneration for these products is in €/MWh and is positive if discharging (i.e. selling) and negative if charging (i.e. buying). Hence, it is up to the BESS operator to utilize the volatility in market prices  $\pi_t^{da}$  to achieve revenues by arbitrage [15]. The objective function (5) models the BESS participation in the DA market, where the operation of the BESS is optimized to charge at the lowest possible prices, then to discharge at peak prices. The bidding resolution is defined by  $t^{da} \in T^{da}$ , which is a temporal set representing one day at a resolution of one hour ( $dt^{da}$ ).

$$\max_{p_t^{da-}, p_t^{da+}} C_{da} = \sum_{t^{da} \in T^{da}} \pi_t^{da} \times (p_t^{da+} - p_t^{da-}) \times dt^{da} \quad (5)$$

### C. Frequency containment reserve (FCR)

FCR is conventionally provided automatically by controllable generation units. The local automatic control system measures the frequency deviation and reacts within 30 seconds after the frequency disturbance [16]. The control system measures the frequency deviation at every time step. Then 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) [17]. In the European Market, the FCR product is symmetric with a 4h duration [18]. The BESS owner gets remunerated for the reserved capacity ( $p_t^{reserve}$ ) in €/MW. Also, there is a remuneration for the actual upward

regulation ( $p_t^{fcr+}$ ) and a cost for the downward regulation ( $p_t^{fcr-}$ ) in €/MWh [16]. 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 minutes [6]. That leads to constraints on the state of charge in the operating phase.

Similar to the participation in the DA market, the FCR bidding and provision takes the form of an optimization problem. In (6), the BESS maximizes the reserve profits while decreasing the cost of downward regulation. Historical data is used to evaluate the revenue with the reserve prices, activation prices, and average frequency deviations over 15 min ( $\pi_t^{reserve}$ ,  $\pi_t^{fcr}$ ,  $\Delta f_{t^a}$ ). The temporal set  $t' \in T'$  represents one day (at a resolution of 4 h), and  $t^a \in T^a$  is a subset of  $T'$  with a resolution of ( $dt^a = 15$  min). The FCR reserve is limited by the BESS power capacity as shown in (7). The 15-minute criterion rule is presented in (8), where the reserve is also limited by energy capacity. The soc limits are calculated in (9) and (10). The activated energy of the FCR is calculated based on the frequency deviations as in (11) – (13).

$$\max_{p_t^{reserve}} C_{fcr} = \sum_{t' \in T'} \sum_{t^a \in T^a} \pi_t^{reserve} \times p_t^{reserve} + \pi_t^{fcr} \times dt^a \times (p_t^{fcr+} - p_t^{fcr-}) \quad (6)$$

$$p_t^{reserve} \leq P_{max} \quad (7)$$

$$E_{cap} / p_t^{reserve} \geq 0.5h \quad (8)$$

$$soc_{max} = 1 - 0.25h \times p_t^{reserve} \times (1 / E_{cap}) \quad (9)$$

$$soc_{min} = 0.25h \times p_t^{reserve} \times (1 / E_{cap}) \quad (10)$$

$$p_t^{fcr+/-} = p_t^{reserve}, \text{ if } |\Delta f_{t^a}| \geq |\Delta f_{max}| \quad (11)$$

$$p_t^{fcr+/-} = (|\Delta f_{t^a}| / \Delta f_{max}) \times p_t^{reserve}, \text{ if } |\Delta f_{db}| \leq |\Delta f_{t^a}| \leq |\Delta f_{max}| \quad (12)$$

$$p_t^{fcr+/-} = 0, \text{ if } |\Delta f_{t^a}| \leq |\Delta f_{db}| \quad (13)$$

### D. Multiple service formulation

The individual participation in energy and reserve market will be assessed with the formulation previously introduced. The jointed participation in DA and FCR is presented in (14), where all objective functions introduced before are summed. The various resolutions of each product are presented in Fig. 1. The final charging/discharging power of the BESS accounts for the DA and FCR contributions in (15) and (16). The latter two equations are used to update the BESS soc at each time step, as introduced in (3).

$$\max C_{total} = C_{da} + C_{fcr} \quad (14)$$

$$p_t^+ = p_t^{da+} + p_t^{fcr,+} \quad (15)$$

$$p_t^- = p_t^{da-} + p_t^{fcr,-} \quad (16)$$

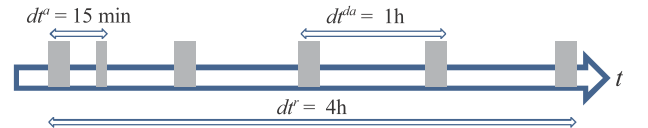


Fig. 1 Energy markets time steps

### E. BESS Oscillation penalty

As previously mentioned, a penalty is introduced in order to control the storage usage and further limit its degradation. As in [19], the penalty accounts for the storage power oscillations between successive time steps along the simulated horizon (17). The oscillations are ultimately penalized with a factor  $\alpha$  and introduced in the objective function in (18). The purpose of this

penalty is to limit the BESS peaks in such a way, the BESS can provide the optimal amount of energy over a longer time with fewer power peaks.

$$\Delta p_j = (p_{j+1}^+ - \tilde{p}_{j+1}^-) - (p_j^+ - \tilde{p}_j^-) \quad (17)$$

$$\max c_{total} - \sum_{j \in J} \alpha \times \Delta p_j^2 \quad (18)$$

### III. SIMULATION AND RESULTS

In this study, the participation of the ESS in the DA + FCR markets is simulated yearly (successive daily optimization) to estimate the revenues and measure the effectiveness of the oscillation penalty. The data were collected for the French market using RTE and Entso-e 2021 databases [20]. A 10 MW/10 MWh BESS is considered with the following parameters:  $\eta^- = \eta^+ = 0.9$ ,  $soc_0 = 50\%$ . Due to the 15-min criterion rule, with a maximum reserve ( $p^{reserve}$ ) of 10 MW, the soc limits are set to  $soc_{min} = 25\%$ ,  $soc_{max} = 75\%$ , according to equations (8) – (10).

#### A. Evaluation of annual revenues

The results from the deterministic annual simulation show that participating in frequency services overperform the energy arbitrage. As shown in Fig. 2, the annual revenues of FCR are three times more than the revenues from DA. That is mainly thanks to the revenues generated by the reserve where the BESS gains money by only guarantying capacity for FCR with no severe effect on its state of charge. The profits of FCR activation are nearly zero due to the almost symmetric activation for upward and downward regulation quantities. Hence, the revenues of upward activation are nearly equal to or less than the costs of downward activation. Furthermore, the analysis reveals that stacking services on a single BESS is the optimum approach to generating maximum revenues. The results show that the profits of stacking DA and FCR are 74 % higher than the sum of profits generated by two separate batteries. The analysis shows that the BESS algorithm uses DA to charge the BESS and utilize this energy to participate later in FCR reserves.

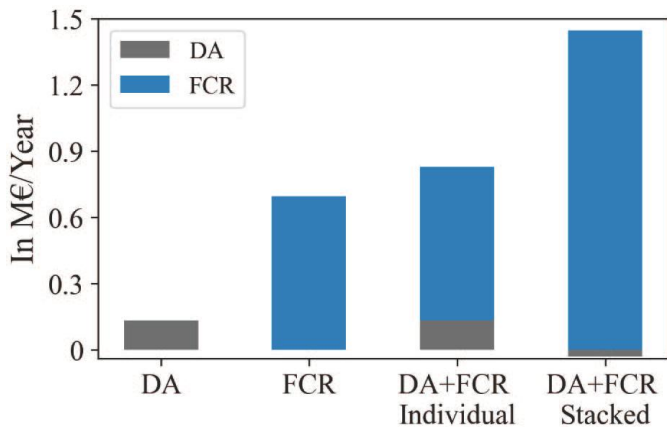


Fig. 2 Annual profits of DA and FCR markets

#### B. Impact of Oscillations Penalty

It was noticed that the BESS soc is affected by providing multiple services at the same time. As can be shown by the grey line in Fig.3(a), the BESS output shows high fluctuations and peak power at several occurrences of the day. That results in an increase in the depth of the discharge (dod) and the degradation of the BESS, as shown in Fig.3(b). With increasing the penalty factor ( $\alpha$ ) the depth of BESS cycles reduces. Also, the peak powers while charging or discharging were avoided by

providing the same amount of energy over a longer time. As example, power peaks between 16h-20h were eliminated using  $\alpha = 20$ . Moreover, the soc was maintained around 50% with small (dod) variations in case of  $\alpha = 100$ .

The analysis in Fig.4 shows the tradeoff between the BESS usage and the yearly expected profit while participating in DA and FCR and for different efficiencies values of the BESS. By increasing the penalty factor  $\alpha$  to 100, the annual revenues decrease by 9 % - 12 % based on the efficiency 0.95 – 0.6. Thus, tuning the penalty factor is vital to keep the expected revenues in a considerable range. The sensitivity analysis also shows that efficiency is positively associated with profits. Moreover, on daily basis, the average reduction in revenues is 6 % while increasing  $\alpha$  up to 100.

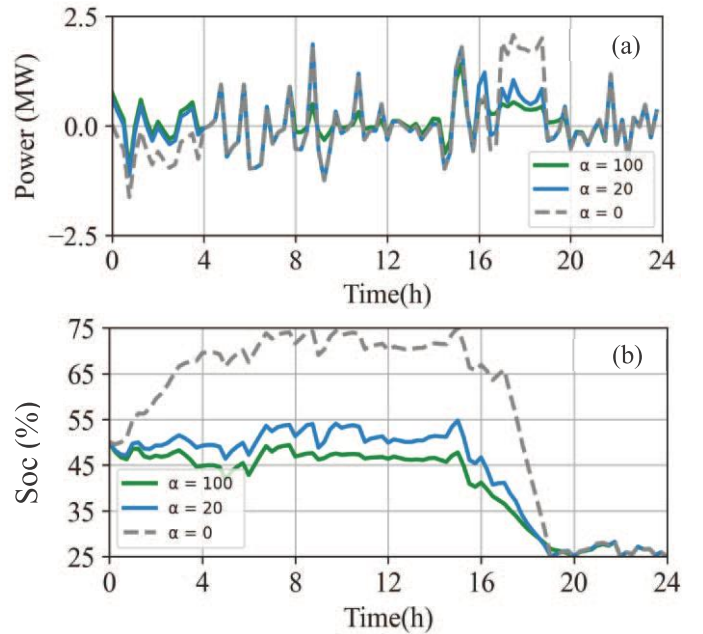


Fig.3 Effect of oscillation penalty on a) the BESS output power, b) the BESS soc profile. (day = 347)

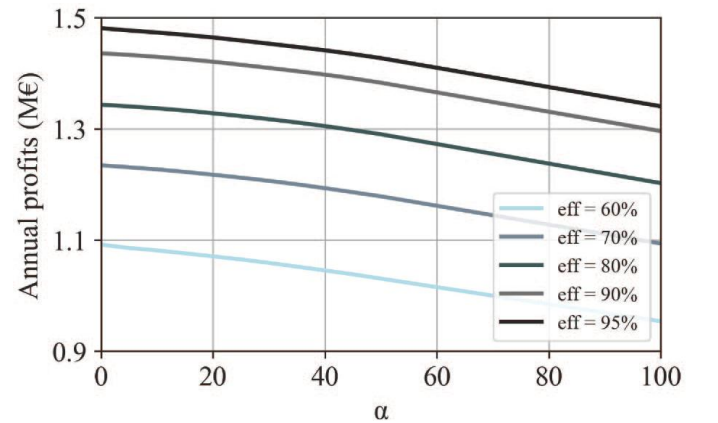


Fig.4 Effect of increasing penalty factor on annual revenues for different BESS efficiencies

#### C. Optimal sizing and Economical Analysis

In this section, a sensitivity analysis is conducted regarding the size of the BESS participating in the DA and FCR markets. Annual simulations are performed by varying the BESS Energy capacity (MWh) while fixing the power capacity (MW). The simulations use the same parameters as those presented in Section 3.1. The Total Cost of Ownership (TCO) is calculated for each BESS size (energy to power ratio) as the difference

between annual costs and the annual revenues ( $r_y$ ). Annual costs include both fixed costs ( $c_0$ ) and operational costs ( $c_y$ ). The fixed costs have been calculated based on the energy capacity to represent the BESS cost and the power capacity to represent the converter costs [19]. Since fixed costs are assessed over the project's lifetime ( $N_y$ ), this analysis discounts them into annual payments. A discount rate ( $i$ ) is equal to the sum of the interest rate and inflation rate is used to discount the total annual fixed costs. Additionally, the operational cost ( $c_y$ ) is estimated at 2.5% of the fixed cost of electrical capacity [20]. The annual revenues ( $r_y$ ) signifies the annual BESS revenues derived from both the DA and FCR markets. The complete formulation of the TCO is introduced in Equation (19), along with the economic parameters of the BESS as presented in Table 1.

$$TCO = \underbrace{\frac{c_0 \times i}{1 - (1+i)^{-N_y}}}_{\text{Annual costs}} + c_y - r_y \quad (19)$$

The findings depicted in Fig. 5 demonstrate that profits significantly increase while moving the energy to power ratio from 0.25h to 0.5h BESS. However, no change is noticed with further increasing the BESS size. This is due to the 15 min that limits the BESS of further participation in the FCR market. Thus, same reserve is committed even with greater energy to power ratio size of BESS. On the other hand, the cost of the BESS is nearly linear with the size. The analysis shows that positive revenues area is only between 0.25h and 2h energy to power ratio. After increasing the energy to power ratio more than 2h, the total revenues are negative. The simulation reveals that the optimal sizing entails a 10 MW, 5 MWh BESS, 0.5h energy to power ratio BESS. This size achieved annual total cost of ownership equals to 756 k€.

Table 1 BESS parameters for sizing and economical analysis

	Value
BESS fixed cost ( $c_0$ )	300 €/KWh, 300 €/KW [19]
BESS operational cost ( $c_y$ )	8 €/KWh [19]
Lifetime guaranteed ( $n$ )	10 years [19]
Interest rate	3.5 % [20]
Inflation rate	2.07 % (2021 year)
Depreciation rate ( $d$ )	12% [20]

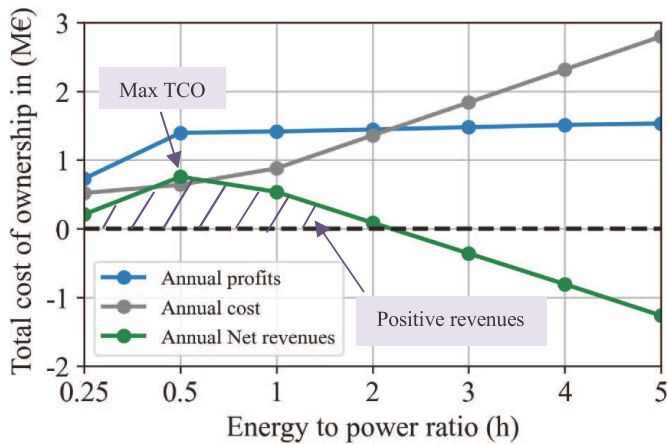


Fig. 5 Sensitivity analysis for different ESS sizes Vs Total cost of ownership

An economic analysis is conducted to assess the different positive revenues sizes that were identified in the previous section. The Net Present Value (NPV) metric is employed for anticipated future cash flows generated by the project, incorporating both the initial investment costs and the expected revenue streams throughout the project's lifespan [22]. The NPV

is calculated using (20). with  $C_0$  the initial cost encompassing both the BESS and power converters,  $C_y$  the yearly operational cost,  $i$  the discount rate, encompassing a combination of the interest rate and inflation rate.  $t$  denotes the year number,  $n$  indicates the projected BESS lifetime, and  $s_n$  reflects the salvage value of the storage system at the conclusion of the project. Importantly, the residual value,  $s_n$ , is closely tied to the BESS's depreciation rate ( $d$ ), which can be determined using the corresponding formula in (20).

$$NPV = -c_0 + \sum_{y=0}^{N_y} \frac{r_y - c_y}{(1+i)^y} + \underbrace{\frac{c_0 \times (1-d)^{N_y}}{(1+i)^{N_y}}}_{\text{The salvage value}} \quad (20)$$

The NPV analysis was conducted for the four profitable energy to power ratios sizing 0.25h, 0.5h, 1h, and 2h. The BESS power capacity was fixed at 10MW while changing the energy capacity. The simulation at section 3.1 was repeated for each BESS size to calculate the annual profits for both DA and FCR markets. The results shown in Fig. 6 indicate that all cases yielded positive NPV values after 10 years, thereby validating the profitability of the project in providing multiple services. Furthermore, the analysis reveals that the optimal sizing led to a shortest payback period of four years. The usage of oversized BESS increase the payback period up to 8 years. This is due to the huge increase of costs, while the increase in profits is insignificant.

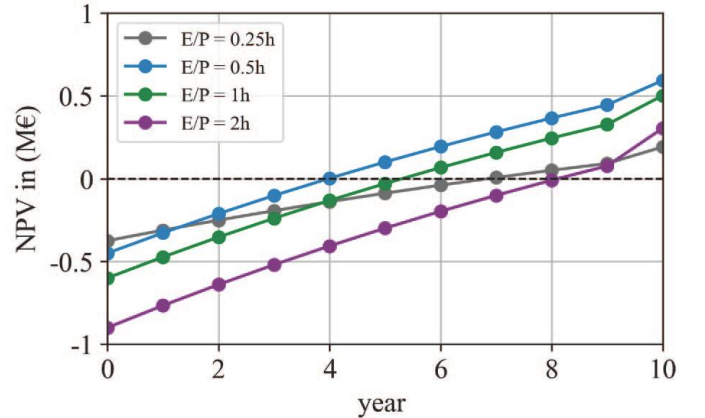


Fig. 6 Economical assessment using NPV for different BESS sizing

#### D. BESS degradation analysis

Although BESS aging is not at the core of the proposed paper, a degradation model developed by [22] is used to evaluate the capacity fade behavior of each BESS sizing. 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 ( $m$ ), as shown in (21). 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 (22). 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.

$$c^{loss, cal} = 0.1723 \times e^{0.0073 \times soc^l} \times m^{0.8} \quad (21)$$

$$c^{loss, cyc} = 0.021 \times e^{-0.0194 \times soc^{av}} \times dod^{0.716} \times n^{0.5} \quad (22)$$

The results of the simulations for the BESS degradation behavior is presented in Table 1. The analysis was performed for the optimal BESS size with energy to power ratio equals 0.5h. Both DA and FCR markets were stacked in the BESS operation. The degradation was calculated over 10 years and the same annual soc profile was fed successively to the model using correction factors to calculate the accumulated capacity fade [22]. As discussed before, in section 3.2, the increase of the penalty factor leads to a reduction in the annual profits. On the other hand, it enhances the BESS lifetime by reducing the capacity fade. Depth of discharge (dod) is the main factor of cycling ageing. As the penalty factor ( $\alpha$ ) increases, the dod of the BESS decrease and hence the capacity fade. The analysis reveals that by increasing  $\alpha$  to 100, the capacity fade reduces by 7 %, while decreasing the annual revenues by only 9 %.

Table 2 BESS degradation behaviour and economical analysis comparison

Penalty factor	Capacity fade	Annual profits
$\alpha = 0$	20.5 %	1,417,966 €
$\alpha = 20$	16.1 %	1,406,245 €
$\alpha = 50$	14.9 %	1,368,789 €
$\alpha = 100$	13.8 %	1,281,045 €

#### IV. CONCLUSIONS

This work investigate the engagement of a grid-connected BESS Energy Storage System (BESS) in the European Day-Ahead (DA) and Frequency Containment Reserve (FCR) markets. By means of annual simulations, the study underscores the remarkable revenue potential derived from delivering multiple services (DA+FCR) via a singular BESS, resulting in a substantial 74% augmentation when compared with discrete market participation. Moreover, a sensitivity analysis is conducted to ascertain the optimal BESS size based on the total cost of ownership for the investment. A 0.5h energy to power ratio was selected as optimal point that achieved 4 years payback period. The incorporation of an oscillation penalty mechanism effectively mitigates BESS degradation by curbing the depth of discharge, thereby reducing BESS capacity fade by 7 %, while incurring a mere 9 % marginal loss in annual revenue.

#### V. FUNDS AND COOPERATIONS

This work was performed in the frame of the project OSS platform, financed by La Région, Auvergne Rhone Alpes, France. This project has received funding from the European Union's ERDF (European Regional Development Fund).

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