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Research Article

Revenue Stacking for BESS: Fast Frequency Regulation and Balancing Market Participation in Italy

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Battery energy storage systems (BESS) are considered a relevant flexible resource for supporting the balancing of a RES-penetrated power grid. Since their cost structure is characterized by very high capital costs, it is of utmost importance to ensure efficient and effective operations from a techno-economic perspective. The possibility of services (and revenues) stacking is one of the most discussed optimization solutions. The present work provides a novel approach for BESS modeling, including the stacking of two diverse ancillary services, a dedicated balancing market bidding model, and a state-of-charge management strategy. Fast frequency regulation is proposed as a power-based service, requiring large ramping capability, but asking BESS activation just for a limited amount of time. For the remainder, BESS power can be traded on balancing market (BM): energy-based services, such as tertiary regulation, could be effectively coupled with power-based, fast regulations, increasing the economic attractiveness of investments in BESS. The case of fast reserve (FR), a new high-speed frequency response service proposed by the Italian TSO in Italy, is assessed in this study. FR provision foresees a capacity-based remuneration (k€/MW/year) and requires to ensure 1000 hours per year of availability. After assessing its cost-effectiveness as a stand-alone service, a sequential multiservice strategy is proposed, where BESS provides FR for 1000 hours, while for the rest of the time it is dedicated to the provision of replacement reserve (RR). Performances of BESS are evaluated considering the reliability of the provision, its operational efficiency, and investment's economics. Performed tests demonstrate how, within the current Italian regulatory framework, the investment's rate of return improves thanks to the multiservice approach. In particular, while maintaining a proper reliability, the minimum acceptable remuneration from FR yearly auctions decreases by 13%; at the same time, self-dispatching of energy through BM calls reduces the need to purchase energy on day-ahead market and keeps BESS state-of-charge far from saturation regions, thus also increasing its lifetime.

1. Introduction

The growing volume of inverter-based renewable energy source (RES) plants is impacting on power system operations, particularly harming their security and frequency stability [1]. As introduced in [2] and detailed by Irena in [3], the higher variability and lower inertia of a RES-based system could be handled by faster and more accurate power control and balancing services. In such a scenario, battery energy storage systems (BESS) are one of the best candidates for system flexibility provision [4], since they feature a fast dynamic response, being power converter-based

systems [5], and thus they are suitable to provide precise and very fast frequency regulation. Irena, in [6], confirmed the fact that most of BESS-installed capacity as of 2020 is devoted to frequency regulation or to ancillary services provision. This trend is expected to continue since many countries are designing new services suitable for BESS (or even tailor-made). This is the case of US' RegD [7], of Germany's frequency containment reserve (FCR) [8], of UK's enhanced frequency response (EFR) [9], and of Italian fast reserve (FR) [10]. Because of this, it becomes fundamental to investigate the best configurations for BESS operations from the techno-economic standpoint,

considering the modeling of BESS's performances, optimal assets' control strategies, and suitability of flexibility services provided.

While in the past, the levelized cost of storage (LCOS) for BESS could not compete with conventional storage technologies, such as pumped hydro-energy storage and compressed air energy storage [11], costs have performed a rapid decrease and they are foreseen to significantly drop in the third decade of 21st century, as highlighted by NREL in [12]. In particular, in [11] it is shown how LCOS decreases when the number of yearly cycles performed increases; this can be achieved, for example, by stacking more services on the same asset. Different approaches are proposed in the literature for services stacking on BESS. In [13], authors present a MILP-based scheduling for a utility-scale BESS to minimize both the impact of outages and energy costs; these targets are reached stacking on the same asset of three logics: grid resilience improvement, network upgrade deferral, and energy arbitrage. The economic benefits of parallel revenue streams, including primary frequency regulation, peak-shaving, and energy arbitrage, are assessed in [14]: through a linear program, considering a small and medium enterprise (SME) context, authors show that when combining three revenues, a BESS can become economical. In its conclusion, however, the paper calls for an improvement in modeling of BESS performances. In [15], authors present a model for assessing the profitability of multiple services stacking; they include frequency containment provision, together with peak-shaving and energy arbitrage. They implement a multiuse, rolling-horizon optimization which dynamically allocates BESS capacity on behind-the-meter of front-of-the-meter services. Some works focus on the simulation of BESS operations within a specific context, such as in [16] where authors consider energy arbitrage and frequency containment provision subject to the rules applied in Ireland. In some cases, such as [13], frequency regulation provision is treated as a black box: frequency-related power simply results unavailable for other purposes, without explicitly modeling the corresponding set-point evolution, while the remaining battery capacity is allocated between different services. The role of BESS siting on the power system becomes fundamental when coping with network limits. In [17], batteries are exploited, together with demand response and dynamic thermal rating, to reduce peak loads and increase network reliability. Also in [18, 19] BESS is used, coupled with thermal rating, to avoid wind or solar power curtailment, solve network congestions, and increase quality of service. Finally, researchers in [20] focus also on the possibility to aggregate energy consumption and production units, coupled with storage devices, in order to co-optimize them within a smart grid context. In this case, BESS is used also to cope with renewable variability by means of a heuristic algorithm.

A proper accuracy in modeling of BESS performances is needed when simulating the provision of fast regulation services, since it is requested to ensure a proper service reliability and effectiveness. Most of the works proposed in the literature focus on electrochemical processes, looking for an extremely accurate simulation of cell chemical characteristics; on the contrary, a minor focus is posed on modeling power conversion systems (PCS) and auxiliary systems (e.g., HVAC), even though they account for a non-negligible share of overall losses, as highlighted in [16, 17]. Indeed, a simple BESS model with a constant charge and discharge efficiency is often accepted, such as in [21, 22]. Moving from these considerations, the first main contribution of this study is to couple services stacking together with a detailed modeling of BESS performances. Optimal operations are evaluated implementing three different set-points, associated with state-of-charge management, fast frequency regulation, and replacement reserve (i.e., tertiary regulation). Considering the current economic and regulatory framework for the Italian electricity market, peak-shaving and energy arbitrage have been neglected, but they will be the subject for future analyses once the Italian electricity market reform is completed. Also, when focusing on rapid frequency containment, the siting of storage assets on the transmission network becomes negligible; on the contrary, this should be carefully assessed when exploiting BESS for congestion resolution or line thermal rating, which is left to future analyses.

Beyond BESS modeling, a further contribution of this study relates to the simulation of electricity markets' dynamics. This is important to fairly evaluate both the technical feasibility and the economic attractiveness of BESS investment. The output targets concern the following:

(i) the quantification of a power set-point requested to the BESS and relevant to a specific market service;

(ii) the quantification of the revenue streams associated with services provision.

Ancillary services markets (ASMs) have been implemented within Europe under different frameworks, having diversities in terms of market products traded, technical requirements, remuneration structure, and session timeline. Consequently, although some characteristics of the dispatching services could be considered common to all EU markets, market dynamics and economics are country dependent; this imposes to focus on specific market products within the context of a given country. The case of the Italian balancing market (BM) and the provision of the tertiary reserve, corresponding to ENTSO-E replacement reserve (RR) [23], is hereby considered. This service was traditionally provided by conventional, large-scale generators; recently, the Italian Regulatory Authority ARERA promoted the opening of the Italian BM to distributed energy resources (DERs), such as small-scale cogeneration plants, smart energy districts, RES, and BESS [24]. Up to 2020, Italian BM was based on six market sessions, each of which lasts 4 hours. Market players should provide hourly bids for upward and downward services separately (featuring a quantity in MW and a price in €/MWh). For each hour, a bid could be rejected, partially accepted (i.e., awarded for a fraction of the bid quantity), or completely awarded. In case of acceptance for the provision of upward service, downward bid is automatically rejected and vice versa. A schematic summary of

Italian BM sessions is provided in Figure 1: the first session contracts energy from 0 AM to 4 AM of day D, and it closes at 11 PM of $D - 1$; the second session contracts 4 AM to 8 AM, and it closes at 3 AM; and so on. The service compliance for RR is verified based on the overall regulating energy provided within 15-minute intervals.

In the literature, most of the analyzed studies do not include the market risk, namely, the risk of having bids rejected (i.e., not selected) by the system operator. However, properly evaluating such issue is pivotal since it influences both the profitability of BESS operations and its reliability in services provision: for instance, if a downward bid (to charge the battery) is not accepted on the balancing market while the battery has low SoC, the energy content of the battery could be depleted, and the battery is no more prompt to provide upward services in the following time slots. Few works focus on the integration of market modeling and energy asset operations, looking for a comparison of the different approaches to simulate BM [25]. The second main contribution of the work is hence to provide a detailed analysis about how economics of a battery system could be influenced by market dynamics. This is done properly assessing market's acceptance rate based on historical prices registered on the Italian BM sessions.

Differently from tertiary regulation, fast reserve (FR) is not traded on the Italian BM: indeed, FR resources are procured by the TSO through specific capacity auctions for a period of 5 years [10]. Each market player can submit an offer for a capacity payment (in k€/MW/year), also reporting a corresponding qualified power (P_{qual} in MW): a P_{qual} from 5 to 25 MW is admitted. A cap for bids' price has been set to 80 k€/MW/year, and FR capacity is assigned with a pay-as-bid mechanism based on economic convenience (cheapest bids are awarded). It is worth noting that auctions are technology neutral, but given the technical requirements imposed for FR provision (e.g., full activation within 1 second), admitted resources should be programmable power converter-based systems. FR service is requested during 1000 hours per year, and it is split in a nondefined (i.e., the information is not defined in the public tender) number of so-called availability blocks along the year (no later than 24 hours before the real-time operation, the TSO will ask the selected resources to activate the service).

Considering this framework, the scope of this study is to assess the technical and economic performances of a BESS providing multiple front-of-meter services, including fast frequency response and tertiary regulation. To do this, two case studies are presented: the reference case includes the provision of only fast reserve, while another one considers the sequential provision of both FR and RR. The main added value of the proposed analysis consists in the integration of a comprehensive tool for the techno-economic assessment of asset operation within a data-driven market modeling. This is done including in the same work.

(i) an accurate and comprehensive BESS model,

(ii) a market model specifically developed on the national BM,

(iii) a detailed modeling of a fast frequency regulation service control strategy and of the BESS control management.

The outcome of the study consists in the evaluation of the optimal bidding strategy for Italian FR auctions as a function of BESS CAPEX.

The paper is structured as follows. Section 2 describes the adopted methodology, including BESS and BM models. Section 3 presents obtained results, with a focus on energy flows, reliability of the service provision (in terms of non-provided power), and economics (internal rate of return).

2. Methodology Proposed

The proposed methodology consists in long-term (1 year) transient simulations of BESS operations with an empirical model developed by the authors [26]. Two case studies will be analyzed, listed below.

(i) In the reference case (case "FR-only"), the BESS provides only fast reserve during the availability blocks (1000 hours per year) and stays idle for the rest of the time. To grant a proper reliability, respecting the technical prescriptions of the grid code, the battery gets to target SoC (55%) 1 hour before the starting of each availability block. In any case, a long idle time and the prevision of a single service potentially decrease the efficiency and economic profitability of the investment [14, 17].

(ii) A multiservice strategy is then proposed, including the provision of RR (tertiary frequency control) on the Italian BM. In particular, RR is provided outside the FR availability blocks, up to 1 hour before their initiation, when SoC management strategy is activated. RR bids are calibrated based on the currently available capacity of the BESS, computed within the RR scheduler of the BESS model. Finally, the acceptance of the bids is based on a BM model fed with statistical data of the Italian BM.

The procedure is implemented in a Simulink tool, gathering the control strategy-related algorithms and the BESS model. The frequency sampled in the Italian electric grid is over-imposed to the BESS model, the BM model is solved, and, consequently, the BESS power output is obtained; finally all the energetic and economic variables are calculated. Figure 2 presents with a block diagram the adopted scheduling procedure. The scheduler is updated based on the considered case study. In particular, the FR-only case includes (in black) the SoC management, whose output is the power requested for SoC management (P_{mgmt}); and the FR control block, whose output is the requested power for FR (P_{FR}). The multiservice case also includes (in grey) the RR control, which returns the bid power for RR (P_{bid}); and the BM model, whose output is the award or rejection of the bid (a Boolean). The output of the scheduler is the power to be exchanged with grid (P_{grid}) that is added to the auxiliary system power (P_{aux}) to give the power requested to the BESS (P_{req}), sent as input to the BESS
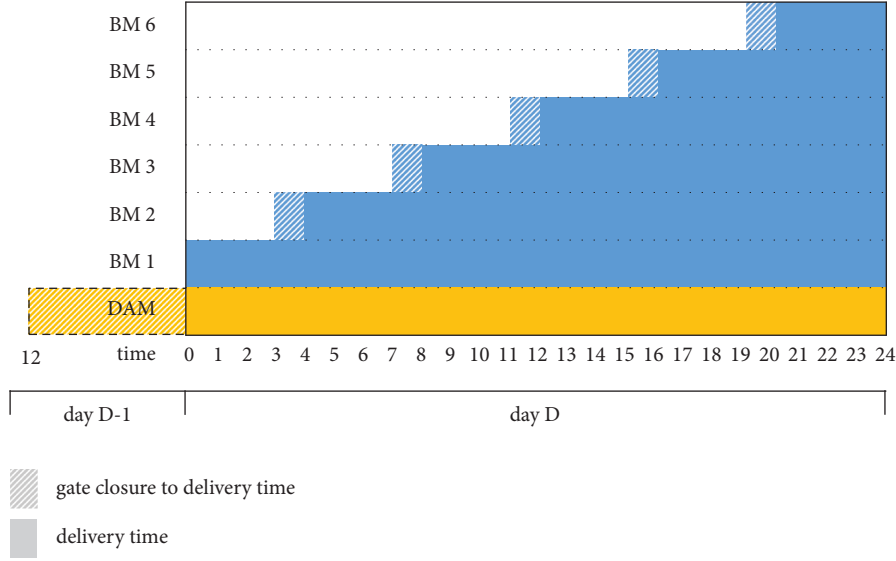
FIGURE 1: Italian electricity markets' timeline, representing the day-ahead market (DAM) and the different balancing market (BM) sessions.
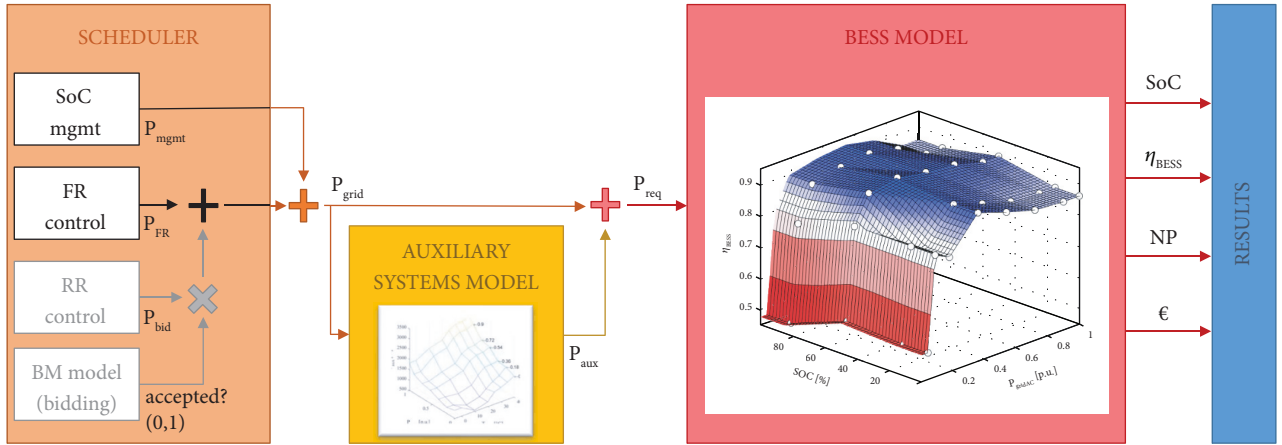

FIGURE 2: Block diagram explaining the procedure implemented for revenue estimation.

model. Main outputs of the BESS model are the SoC, the BESS efficiency ($\square_{\text{BESS}}$), the nonperformance (NP) in the provision of ancillary services, and the cash flows.

2.1. BESS Modeling.

The adopted BESS model presents a variable BESS efficiency as a function of the battery state-of-charge (SoC) and of the requested power, also including the losses in the power conversion system and BESS auxiliary demand. Thanks to a verification and validation procedure, as reported in [26], its accuracy in estimating the SoC evolution of a real-world asset is estimated higher than 98%. The empirical model emulates BESS operations based on the following:

(i) Performances of battery and PCS,

(ii) A capability chart indicating the maximum available power at different SoC levels,

(iii) A model dedicated to the auxiliary system consumption as a function of ambient temperature and fluxed power (P_{req}).

Moving from the analysis presented in [26], the present study extends the efficiency look-up table considering energy-to-power ratios (*E/P*) up to 0.5 h.

Figure 3 presents the empirical surface used to estimate BESS efficiency: it is possible to see that the latter shows a dependency on both SoC and requested power.

BESS characteristics considered for the study cases are presented in Table 1. As said, an EPR of 0.5 h is considered, with a 5 MWh/10 MW storage. Considering the rules drawn by Italian TSO for FR provision, a qualified power of 8 MW is defined. Correspondingly, a capacity of 2 MW can be exploited for SoC management.

2.2. BESS Scheduling Strategy.

The scheduler of the BESS model is developed in the framework of this study to host the following:

(i) The FR control;

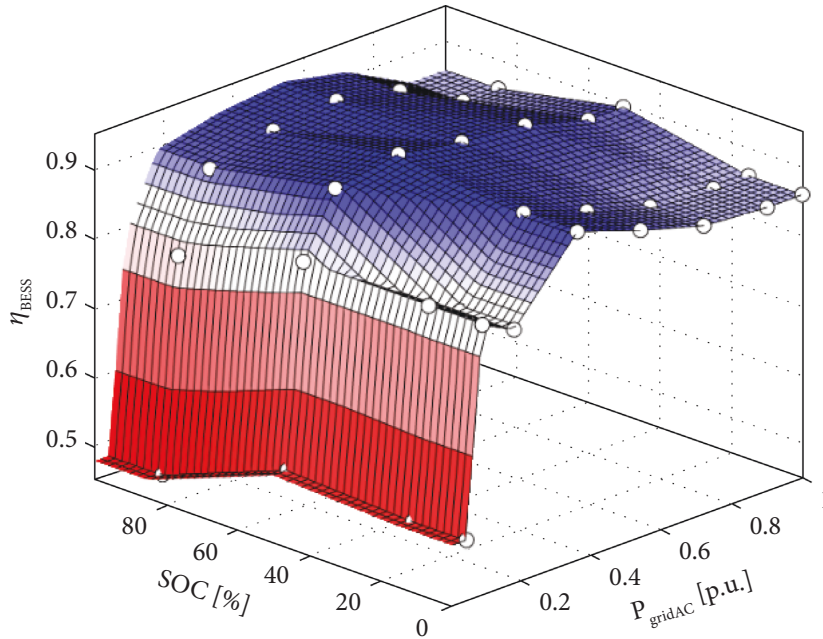(ii) The SoC management strategy (a dead-band strategy coherent with grid code prescriptions);

FIGURE 3: Surface representing BESS roundtrip efficiency.

TABLE 1: BESS characteristics considered in the study case.

Key	Value	Unit
Nominal energy (E_n)	5	MWh
Nominal power (P_n)	10	MW
Qualified power (P_{qual})	8	MW
SoC management power (P_{mgmt})	2	MW
Target SoC (SoC_{target})	55%	%

(iii) The RR control;

(iv) The bidding strategy on BM for RR provision, including the BM model.

The listed components of the scheduler are described in the following.

2.2.1. Fast Reserve Control. This block implements the control strategy for the FR. It is schematically presented in the flowchart of Figure 4. A local power system frequency measure (referred to Continental Europe Synchronous Area), with a sampling rate of 1 second, is used to calculate the frequency deviation with respect to the target value of 50 Hz; this is converted into a power set-point through the droop curve presented in Figure 5 and is imposed to the BESS as reported by Algorithm 1.

During an availability block, the qualified resource must provide frequency response based on the droop curve presented in Figure 5 (left part) in which a dead band (level #1) as well as a full activation threshold (levelSAT) are defined. If the frequency deviation does not get larger than a second threshold (level #2), BESS is allowed to stop the dynamic frequency response after 30 seconds and start a fade-out of 300 seconds (see right part of Figure 5). This is because the FR is power-intensive and therefore the control strategy aims to

save the energy content of the participating resources. Vice versa, if the frequency deviation is larger than level #2, the power system is supposed to be in emergency conditions and therefore resources are requested to continue providing their dynamic response. FR rules also include the possibility of SoC management within the availability blocks, following a dead-band strategy: while the frequency deviation is within the dead band, the battery can offset its power set-point by 0–25% of P_{qual}, to get the SoC back to a target SoC (e.g., 50%). The energy flows for SoC management are valorized at the day-ahead market (DAM) price, for both charging (to pay) and discharging (to receive) phases.

It is possible to see that the fade-out, induced after 30 seconds of noncritical frequency deviation, is interrupted if critical conditions are reached (deviation above level #2) or if frequency deviation changes its direction (from over- to underfrequency or vice versa).

With respect to the service duration (i.e., the minimum amount of time the BESS is asked to guarantee the service, resulting in a constraint to the minimum BESS energy content), FR rules require a minimum provision of 15 minutes at the qualified power for each service session, which lasts for two hours. For values above this energy requirement, the FRU is authorized to suspend the FR provision. This is to limit the required energy content, coherently with the power-intensive nature of FR. The main values for BESS dynamic response are detailed in Table 2.

With respect to the identification (and the simulation) of the FR blocks (1000 hours per year where the TSO will ask the activation of the FR service), a probabilistic analysis has been performed. In particular, the frequency profile registered for Continental Europe Synchronous Area in 2016 has been considered. Supposing that the TSO would ask for the FR service when it needs it the most, hence in the most
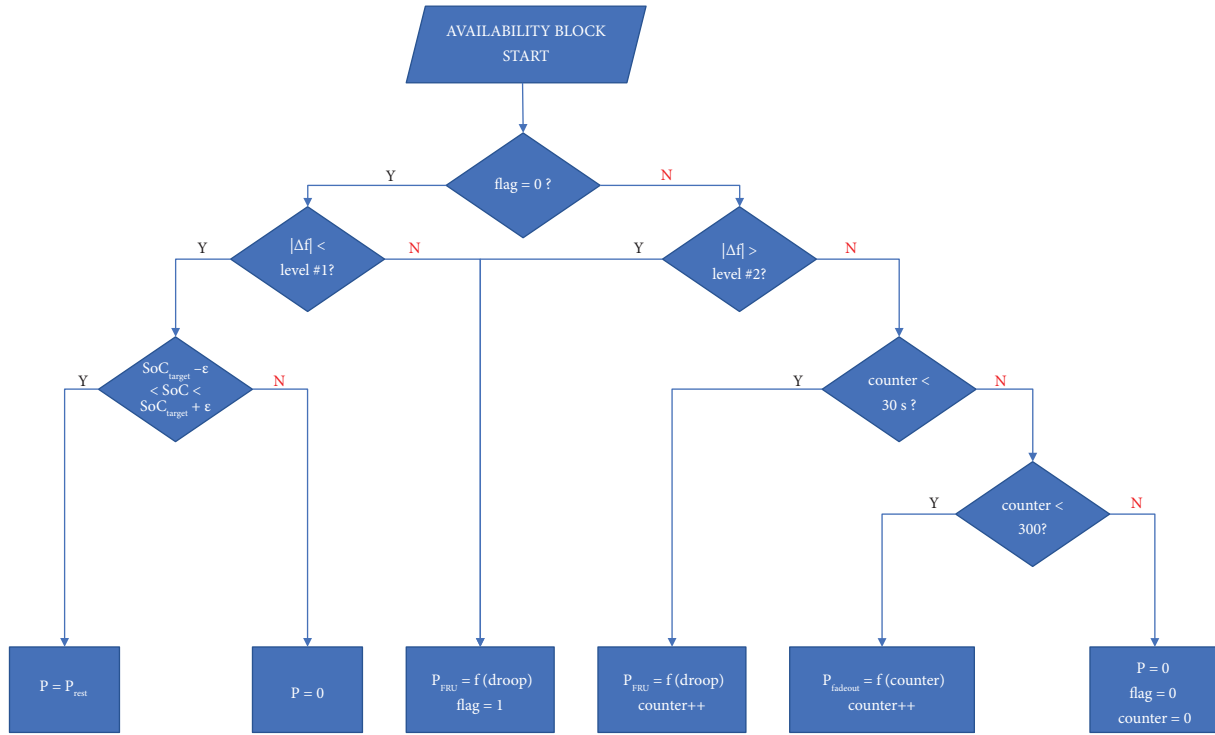
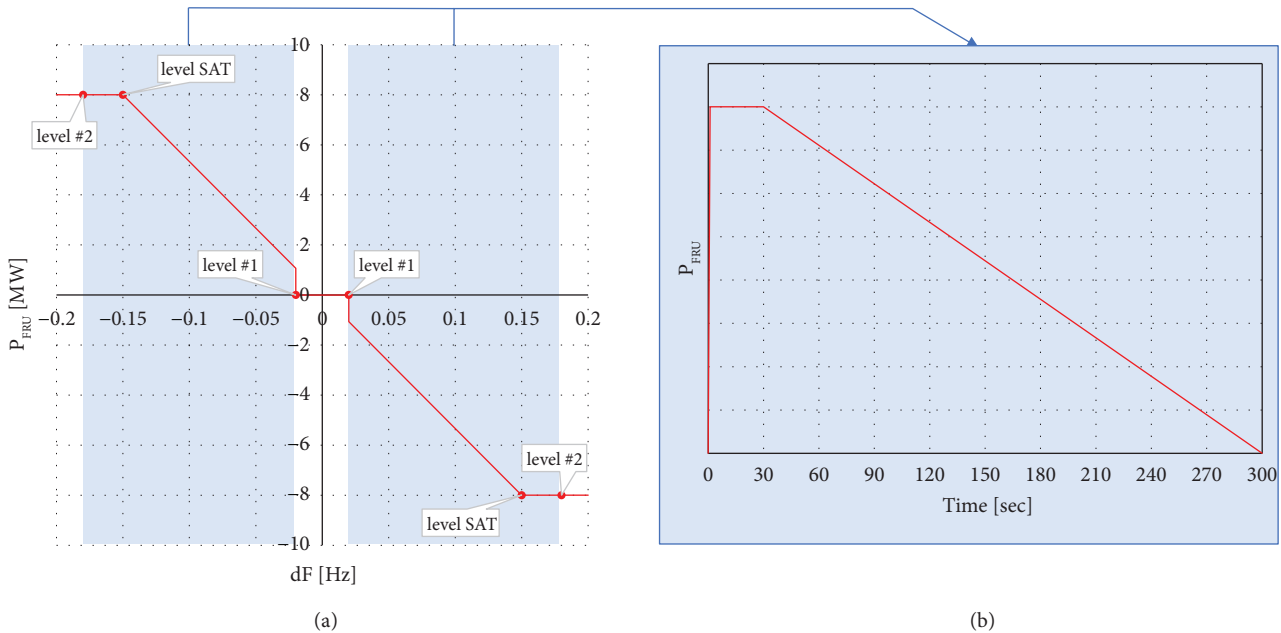FIGURE 4: Fast reserve BESS scheduler flowchart.

(a)

(b)

FIGURE 5: Fast reserve droop curve (left) and fade-out curve (right).

demanding frequency conditions for the BESS, availability blocks have been determined selecting the 100 nonoverlapping most demanding 10-hour intervals, as described by Algorithm 2. This results in a set of availability blocks for which there is the largest cumulative frequency deviation in 2016.

The yearly frequency profile for 2016 and the availability blocks are reported in Figure 6. In the top part of the diagram, the frequency trend is shown. In the bottom part, the

availability blocks are the vertical red bars. As it can be seen, they are spread all over the year, with a larger concentration in January and October.

2.2.2. SoC Management Strategy. The SoC management strategy is implemented to avoid saturation at minimum or maximum SoC limits (0 and 100%). Following the technical rules of FR provision, the SoC management strategy consists in a dead-

Input: Frequency deviation Δf_t with respect to 50 Hz, measured each second
Output: Power set-point of the BESS for each second within the simulated period *TimePeriod*
counter = 0, j for underfrequency levels, i for over-frequency levels
for t **in** *TimePeriod* **do**
   $P_{\mathrm{FRU}}^{t} \leftarrow$ Apply droop curve
   if *counter == 30* **do**
      Start BESS fade-out from current power set-point P_{FRU} to 0 in 300 seconds
      $P_{\mathrm{FRU}}^{t} \leftarrow P_{\mathrm{FRU}}^{t-1} - P_{\mathrm{FRU}}/300$
   else if Δf_t **is in** [level #1$_j$, level #2$_j$] $\cup$ [level #1$_i$, level #2$_i$] **do**
      Increment the counter
      counter $\leftarrow$ counter + 1
   else *counter = 0*
   if $\Delta f >$ level #2$_i$ (level #1$_j$) **or** $\Delta f >$ level #2$_j$ (level #1$_i$) **do**
      $P_{\mathrm{FRU}}^{t} \leftarrow$ Apply droop curve
      counter = 0
return BESS power set-point P_{FRU}

ALGORITHM 1: BESS FR set-point management.

TABLE 2: Fast reserve requirements influencing BESS dynamic response.

Key	Value	Notes
Dead band (level #1)	±20 MHz	
Full activation (levelSAT)	±150 MHz	
Emergency threshold (level #2)	±180 MHz	Above this threshold, fade-out is disabled.
Fade-out trigger	30 s	In case the Δf remains this time within level #1 and #2, a power deramping starts.
Fade-out duration	300 s	
Maximum energy delivered	15 equivalent minutes	In 2 hours, this is the maximum energy content that can be requested to the FRU.

Input: Cumulative hourly frequency deviation with respect to 50 Hz in 2016 ($\Delta F2016$)
Output: Set of 100 availability blocks for FR provision (FRΔF), each one lasting for 10 hours
$C\Delta F$: 10-hour cumulative frequency deviation blocks
for t **in** $\Delta F2016$ **do**
   Compute the 10-hour cumulative frequency deviation
   $C\Delta F^{t} \leftarrow \sum_{t}^{t+10} \Delta F^{t}2016$
return 8774 blocks of 10-hour cumulative frequency deviation
List the blocks in descending order: $C\Delta F^{t} \longrightarrow C\Delta F^{t}\downarrow$
$FR\Delta F^{1} \leftarrow C\Delta F^{1}\downarrow$, $s = 2$
for c **in** $C\Delta F^{2 \rightarrow 8774}\downarrow$ **do**
   while $s \leq 100$ **do**
      if $C\Delta F^{c}\downarrow$ **is not** *overlapping* **with** $C\Delta F^{1 \rightarrow c-1}\downarrow$ **do**
         $FR\Delta F^{s} \leftarrow C\Delta F^{c}\downarrow$
         $s \leftarrow s + 1$
return 100 availability blocks of 10-hour $FR\Delta F$

ALGORITHM 2: FR availability block selection.

band strategy that is activated whenever the battery has less than 15 equivalent minutes remaining, either in the upward or in the downward direction, within an availability block. Therefore, it has a double threshold check [27], since it activates if:

(i) the ΔF is in the dead-band and

(ii) the SoC is outside a safety window (see below).

The safety window is computed considering an upper (SoC_{hi}) and lower SoC (SoC_{lo}) limits, coherently with a minimum required service duration of 15 minutes.

$$SoC_{hi} = SoC_{max} - P_{qual} * \frac{15}{60} * \frac{1}{E_n} * \eta_{avg} = 63.2\%,$$

$$SoC_{lo} = SoC_{min} + P_{qual} * \frac{15}{60} * \frac{1}{E_n} * \frac{1}{\eta_{avg}} = 43.5\%, \tag{1}$$

where SoC_{max} is 100%, SoC_{min} is 0%, and η_{avg} is the average efficiency of the battery [26], considering the actual SoC variation of the full power activation. Moreover, the SoC management strategy is activated 1 hour before the
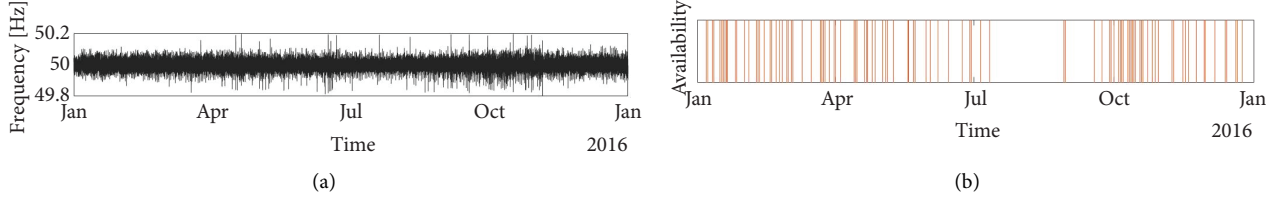
FIGURE 6: Yearly frequency profile (2016) (a) and corresponding FR availability periods considered (b).

beginning of each availability block and deactivates at its end: this 1-hour advance allows to restore the SoC to SoC_{target} at the beginning of each block. The SoC management strategy is summarized in Algorithm 3.

2.2.3. Balancing Market Modeling and Bidding Strategy.

To model the Italian BM, a statistical analysis has been carried out on historical market data about prices and quantities accepted. Italian BM foresees an energy-only payment (€/MWh): units are remunerated to increase their injection (upward regulation), and oppositely they must pay to decrease it (downward regulation). To simulate the market outcome, marginal hourly prices of the year 2017 for both regulations are fed as input to the model: maximum awarded prices for upward regulation and minimum awarded prices for downward regulation. These are the less economically convenient prices (from the system operator perspective) awarded on the market for a specific session This allows to define a distribution of the hourly marginal prices for each regulation, distinguishing working days (Monday to Friday) and holidays (Saturdays, Sundays, and bank holidays). Then, for every simulated hour, in order to simulate the BM outcome, a price is randomly sampled from these distributions (always distinguishing between working days and holydays) and it is fed to the model; this is hence compared to the bid price defined according to the strategy described in the next paragraph. BM marginal price distributions are reported in Figure 7.

In the proposed model, for a specific hour, an upward bid is accepted if the offered price is lower than the maximum awarded, and it is rejected elsewhere. Oppositely, a downward bid is awarded if the bid price is higher than the minimum one (the willingness to pay of the bidder is high), rejected elsewhere. Based on this, the bidding strategy looks at the SoC value at the beginning of each market session. The bid price is determined as the average price historically registered on past market data for that hour, adding or subtracting a component defined as a function of $SoC(t)$. In particular:

(i) if $SoC(t)$ is higher than SoC_{target}, the offered price for upward regulation decreases proportionally to the distance of $SoC(t)$ from SoC_{target}, thus increasing the probability of acceptance;

(ii) for the same reason, if $SoC(t)$ is lower than SoC_{target}, the price offered for downward regulation increases proportionally to the distance of $SoC(t)$ from SoC_{target}.

The bidding strategy for hour h is implemented as in

$$B(h) = \mu(h) - \sigma(h) * \frac{SoC(t) - SoC_{target}}{100}, \quad (2)$$

where $B(h)$ is the bid price for hour h, $\mu(h)$ is the average market price for upward or downward services for that hour, and $\sigma(h)$ is the standard deviation of the corresponding probability distribution. Market prices of upward and downward services are evaluated based on 2017 data. Average values of hourly prices are presented in Figure 8, distinguishing between working days and holidays.

2.2.4. Service Stacking Strategy.

The multiservice strategy considers the provision of RR, according to the Italian BM rules [28], while maintaining also the provision of FR within the availability blocks. Asymmetric volumes of tertiary regulation can be offered on the market, based on the bidding strategy described before.

In particular, the RR provision strategy is designed to allow passive SoC management: this is achievable since the service is asymmetric and the control strategy is set up coherently so that, for example, if the SoC is above SoC_{target} only upward (discharge) service is offered and vice versa.

Focusing on the Italian scenario, RR product is traded on market sessions of 4 hours (t_{mkt}). The BESS operator can bid 4 hourly quantities (in MW) and prices (in €/MWh) for both upward and downward reserves. Following the described bidding strategy, BESS operator bids either upward or downward, depending on the SoC level at the market closure.

The bid volume is defined as in Algorithm 4, where k_{mkt} is a parameter inducing a safety margin on the definition of P_{RR} (for reliability reasons) equal to 1.2. This ensures that even if the bids are awarded for 4 consecutive hours, the SoC threshold is not reached.

Bids are awarded on an hourly basis: if the price offered is more convenient than the marginal accepted price (randomly sampled from the corresponding distribution) of that market hour. Bids cannot be partially accepted: they are either totally awarded (for the total amount of offered MW) or rejected. If awarded, P_{RR} set-point is activated and BESS is supposed to provide a constant power set-point for the whole hour.

2.2.5. BESS Power Control Logic.

Finally, the output of the blocks described above provides a well-defined

Input: Frequency deviation Δf_t and availability blocks of 10-hour FRΔF
Output: Power set-point for SoC management P_{mgmt}
FRΔF_h^s with h from 1 to 10: hours composing the availability block s
for t **in** [FRΔF_0^s; FRΔF_{10}^s] **do**
    if Δf_t **is in** dead-band **and** (SoC > 56% **or** SoC < 52%) **do**
        $P_{mgmt} = 2$ MW
        SoC$^{t+1} \leftarrow$ SoC$^t \pm P_{mgmt}/(3.600 * E_{nom})$
    return SoC management set-point P_{mgmt}
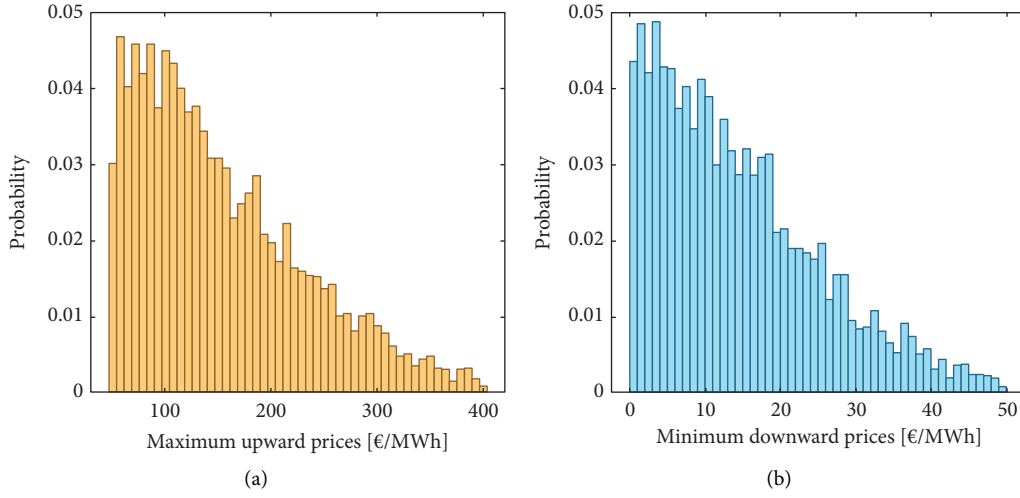
ALGORITHM 3: SoC management procedure.

(a)

(b)

FIGURE 7: Marginal prices coming from the statistical analysis and fed to the model for RR provision: probability distribution of maximum upward prices (a); probability distribution of minimum downward prices (b).
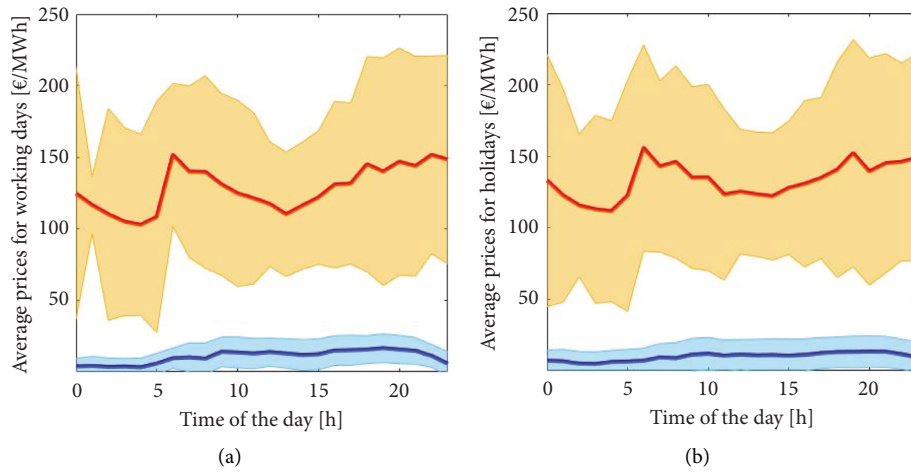

(a)

(b)

FIGURE 8: Average prices for upward and downward regulation in the Italian market (2017 data): hourly prices during working days (a); hourly prices during holidays (b). Red lines are the hourly average upward prices, while blue lines are downward ones. Shaded areas represent the standard deviation.

power set-point. The requested power (P_{req}) can be formulated as in

$$P_{req} = P_{grid} + P_{mgmt} + P_{aux}, \qquad (3)$$

where P_{grid} is the power for the provision of grid services, summing the power for FR (P_{FRU}) and RR (P_{RR}), P_{mgmt} is the power for SoC management, and P_{aux} is the demand of the auxiliary systems. Auxiliary systems are directly fed by the battery and always request positive power proportional to

BESS exchanged power and to ambient temperature. A better detail of the auxiliary system model is given in [29].

2.3. Techno-Economic Analysis.

The two case studies considered are compared in terms of energy exchanged, technical performances, and economics.

2.3.1. Technical Performance Evaluation.

For what concerns energy exchanges, and in coherence with the project rules [30], the following flows are considered.

(i) The energy provided for FR is associated with P_{FRU} as the absolute energy delivered during the availability hours as for the droop curve, including the de-ramping strategy. The high reliability of the provision is a requirement for being awarded with the capacity-based remuneration obtained in the auction (k€/MW/year).

(ii) The energy for SoC management (P_{mgmt}) during the availability hours is valorized at the DAM price, both for charging (to pay) and for discharging (to receive).

(iii) The energy provided for RR is remunerated at the awarded price, coming from the developed market model. In this case, the reliability of provision is important, too. A fee for nonperformance is implemented (energy-based €/MWh).

(iv) The energy for auxiliary systems (P_{aux}) is estimated by the model. This demand is fed either by the battery itself (that self-discharges) or by withdrawal from the grid (this in case the battery is exhausted).

(v) The withdrawal outside the availability hours is treated differently. In this case, since there is no dedicated rule within the pilot project, the withdrawal (P_{with}) is paid at the bill price. This is a conservative choice since the framework in Italy is updating to guarantee that all the energy that is withdrawn for a next reinjection can be paid at the zonal price, as per [31]. The operational performances increase when the withdrawal is reduced through the provision of downward power regulation.

Operational performances are evaluated based on both nonperformance (NP) parameter and operational efficiency. The NP-related power for FR ($P_{\text{NP,FRU}}$) is computed as for

$$
\begin{cases}
P_{\text{NP,FRU}} = P_{\text{FRU}}, & \text{if } \dfrac{\left| P_{\text{req}} - P_{\text{del}} \right|}{P_{\text{req}}} > 5\%, \\[2em]
P_{\text{NP,FRU}} = 0, & \text{elsewhere,}
\end{cases}
\tag{4}
$$

where P_{del} is the power delivered by the BESS AC side. It is equal to P_{req}, unless some limitations on power or SoC are hit. The same computation is performed on NP-related power for RR to obtain $P_{\text{NP,RR}}$. The 5% threshold value is considered in both cases since it is the dynamic precision requested by the pilot project for BESS power output. The integral in time of the absolute value of $P_{\text{NP,FRU}}$ and $P_{\text{NP,RR}}$ results in the NP-related energy for the two services ($E_{\text{NP,FR}}$ and $E_{\text{NP,RR}}$). The NP share (NP_{FRU} and NP_{RR}) is computed by dividing E_{NP} by the total energy requested for the services (E_{FRU} and E_{RR}). The NP must be kept low, since it can be considered the complementary to 1 of the reliability. Generally, a NP below 5% is welcomed [32]. Efficiency is estimated for each computational time step. The average efficiency is considered as a KPI for the study: it is the average of the charging/discharging operational efficiencies experienced by the BESS in each instant of the simulated period. It includes both the battery efficiency and the PCS efficiency. A better management of the BESS could lead to increase the overall efficiency: as an example, avoiding idle periods when only the auxiliaries are active is beneficial [29].

2.3.2. Economic Performances.

Capital expenditures (CAPEX) include the cost of the whole BESS. It is well known that the cost of BESS is related to both nominal energy (the cost of the battery pack mainly) and nominal power (the cost of the PCS) [33]. Nominal energy (E_n) and power (P_n) are linked with the energy-to-power ratio, namely, the ratio between E_n (in MWh) and P_n (in MW). Considering the specific cost k_e (in k€/MWh) for a standard battery with EPR = 1 h, the total CAPEX can be assessed as follows:

$$
\text{CAPEX} = k_e * E_n + \left(P_n - E_n \right) * k_p,
\tag{5}
$$

where k_e is equal to 300 k€/MWh—that is coherent with sources from literature and from commercial insights for a BESS to be commissioned in 2022 [12]—and k_p is equal to 150 k€/MW, being the cost of the PCS following commercial and institutional sources [33]. Following equation (6), for a fixed E_n, the CAPEX increases in case of a P_n larger than E_n (E/P lower than 1, higher c-rates requested) and decreases and vice versa (larger E/P, lower c-rates). The operating expenditures (OPEX) are set to 5 k€/MWh/year, based on commercial and institutional estimations [12, 28]. Further operating costs are related to the energy flows for SoC management (within the availability blocks) and energy withdrawn (outside the availability blocks). As previously described, SoC management within the availability blocks is always valorized in €/MWh at the DAM price, for both charging (to pay) and discharging (to receive). For the remainder, energy is bought at the bill price. In case there is energy injection toward the grid, for instance for restoring the SoC before an availability block starts, it is valorized at 0 €/MWh, considering a severe penalty for the imbalance [34]. The fees for NP are related to FR project rules: in case x % of energy is nonprovided, x% of the capacity-based payment is not delivered. Dealing with FR, the applied imbalance discipline foresees a strong penalization for both upward and downward imbalances: a fee of 100 €/MWh is applied on NP, equivalent to the average awarded price for upward provision in BM [34].

BM-related revenues are equal to the energy requested for RR provision multiplied by the awarded prices in the BM model, being the Italian BM a pay-as-bid market. On the other hand, FR revenues are based on stand-alone auctions. A summary of inputs considered can be found in Table 3.

The economic analysis is carried out based on an investment horizon of 5 years, coherently with the duration of FR project [10]. At the end of the FR project, the net present value (NPV) of the investment is requested to be zero. NPV is computed in equations (5) and (6).

$$\text{NPV} = \text{CAPEX} + \sum_{i}^{N} \frac{\text{NCF}}{(1+r)^{i}} + \frac{\text{RV}}{(1+r)^{N}} = 0, \tag{6}$$

$$\text{NCF} = R_{\text{FR}} + R_{\text{BM}} + R_{\text{dis}} - C_{\text{ch}} - C_{\text{bill}} - \text{NPP}_{\text{FR}} - \text{NPP}_{\text{BM}}, \tag{7}$$

where NCF is the net cash flow for each year considering: positive revenues from FR (R_{FR}) and from BM (R_{BM}), SoC management cost for charging (C_{ch}), revenues for discharging (R_{dis}), energy withdrawal at the bill cost (C_{bill}), and NP penalties for FR (NPP_{FR}) and BM (NPP_{BM}). The residual value (RV) is based on the remaining life of asset, and it is linearly decreasing with respect to initial CAPEX. The estimated BESS lifetime is computed based on the aging model proposed in [38] updated with [39]. In particular, capacity fade is considered: EoL is when the available energy is 80% of nominal energy. RV is computed in

$$\text{RV} = \text{CAPEX} * \frac{(t_{\text{EoL}} - t)}{t_{\text{EoL}}}, \tag{8}$$

where t is the time horizon for the investment. To get NPV = 0 at year = 5, the FR bid is selected accordingly, hence aiming to define the best bid for the FR auction in both the study cases (FR-only and multiservice).

3. Results and Discussion

For each case, a first analysis of BESS operations and of power flows is given. Then, the evaluation of performances and reliability is presented. After that, the economic analysis is proposed, also estimating an optimal bid for FR auction.

3.1. FR-Only Study Case. In the presented simulations, 100 blocks lasting for 10 hours each are supposed to constitute the FR availability blocks. Outside of these availability blocks, the BESS is idle. As it can be seen in Figure 9, a spiky power profile is requested during the availability blocks: this is coherent with the provision of FR. Also, SoC does not deviate largely from target SoC (55%), due to the SoC management strategy that is activated whenever it is above or below the reliability thresholds previously described. On the other hand, battery SoC decreases during idle periods due to auxiliary system consumption. In these periods, the only relevant power is related to the auxiliary demand, which imposes a BESS discharging depending on the ambient temperature and the requested power. Even if this power is

negligible compared to BESS size, being the battery idle, it often leads to approach the minimum SoC. When this happens, auxiliaries are fed by the power withdrawal from the grid.

Even if the qualified power (P_{qual}) to FR is 8 MW (see Table 1), the requested power hardly gets over 5 MW. This is because the full activation threshold (level #2-±150 mHz) is larger than the observed frequency deviations. A focus on FR provision is reported in Figure 10. The frequency profile for some minutes is presented in the top diagram: Δf remains inside the dead band for the first minutes (frequency within 49.98–50.02 Hz); therefore, the scheduler checks the SoC: if it is outside the reliability thresholds (52–56%), the management starts and tries to restore it toward the target SoC (55%), discharging or charging (as in the figure case) the battery. The negative (charging) power for SoC management can be seen in pink in the mid chart: it is equal to 25% the P_{qual}, thus 2 MW. The SoC steadily increases in that time interval. Just after 9 PM (21 : 00 in Figure 10), frequency gets outside the dead band, stopping the SoC management procedure; the FR dynamic response is activated (in orange in mid chart), following the underfrequency event by injecting power into the grid: this is performed respecting the droop curve, proportionally to the frequency deviation. Since the frequency deviation does not get outside emergency thresholds (level #2-±150 mHz), after 30 seconds a fade-out starts, bringing back the FR provision to 0 in 300 seconds.

The grey line refers to auxiliaries' consumption. The auxiliary power demand is always present, even if its size is relatively small (the maximum requested power is around 74 kW). Over the whole simulation (8760 hours), the total energy demand for auxiliaries is 283.4 MWh, representing 34.6% of the absolute energy provided for FR. A large part of this power is withdrawn from the grid, since BESS is often exhausted.

The main technical data for evaluating the FR provision are reported in Table 4. They relate to both energy flows and technical performance. The energy cycled by the BESS is more than 1000 MWh per year, around 120 yearly equivalent cycles.

There is no NP_{FR}, since the power requested is always provided: no limitations due to SoC saturation or capability chart are present. This means that the reliability of the provision is 100%. BESS estimated lifetime is 11.6 years, obtained considering the aging model applied in [38]. BESS efficiency (averagely 75.1%) is very low compared to general values of Li-ion NMC BESS performances [26]: this is because during a large amount of time the battery delivers a very low power with respect to BESS nominal one.

Economic data are proposed in Table 5, where revenues are positive and costs are negative. CAPEX are paid at year 0, with an investment above 2.2 M€ according to (6). OPEX are estimated around 25 k€, not considering the energy flows for SoC management and auxiliaries. Indeed, SoC management implies a yearly net cost around 5 k€, with all flows valorized at DAM price. The energy withdrawn outside availability blocks is instead paid at the bill cost, thus more than 3 times the DAM price. The total cost for energy withdrawal is

TABLE 3: Reference parameters used in economics evaluation for the case study.

| Key	Value	Unit	Reference
CAPEX on nominal energy (k_e)	300	k€/MWh	[12, 33]
CAPEX on nominal power (k_p)	150	k€/MW	[33]
OPEX	5	k€/MW/year	[12, 35]
DAM price	60	€/MWh	[36]
Bill cost	200	€/MWh	[37]
Injection price	0	€/MWh	Worst case based on [34]
FR revenues (R_{FR})	Based on auctioned bid	k€/MW/year	
BM revenues (R_{BM})	Based on market model	€/MWh	
Fee on FR nonperformance	% of capacity-based payment	k€/MW/year	[10]
Fee on BM nonperformance	100	€/MWh	[34]
Actualization rate®	5	%	

(a)

(b)
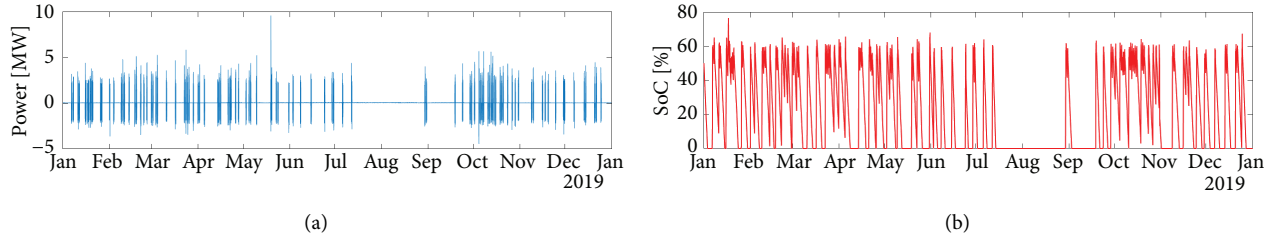
FIGURE 9: Power (a) and SoC (b) simulation results for FR-only case.
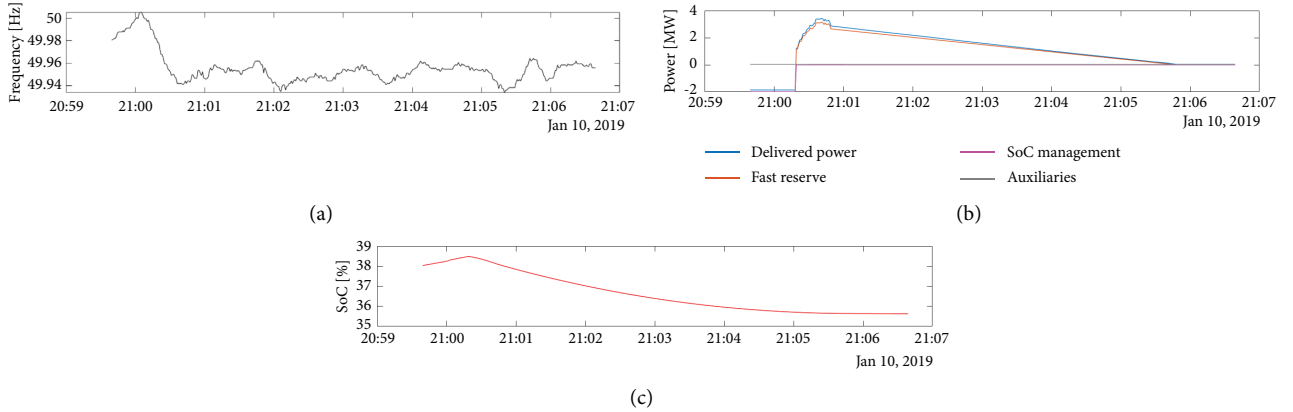

(a)

(b)

(c)

FIGURE 10: Zoom on the operation of BESS in the FR-only case, including frequency variation (a), power management (b), and SoC evolution (c).

TABLE 4: Technical results from FR study case.

Key	Value	Unit
Total energy cycled	1.167	MWh/y
FR provision	819	MWh/y
SoC management (charging)	167	MWh/y
SoC management (discharging)	86	MWh/y
Auxiliary demand	283	MWh/y
Energy withdrawal	238	MWh/y
NP$_{FR}$	0	%
BESS estimated life	11.6	years
Average efficiency	75.1	%

TABLE 5: Economic results for FR study case.

Key	Value	Unit
CAPEX (year 0)	−2250	k€
OPEX	−25	k€/y
NPP_{FR}	0	k€/y
SoC management costs (charging)	−10	k€/y
SoC management revenues (discharging)	5	k€/y
Bill total cost	−47	k€/y
Residual value (end of year 5)	1283	k€

therefore 47.5 k€. There is no penalty for NP_{FR}, since there is no NP_{FR}. At the investment's time horizon (5 years), still more than half of BESS value is residual (1.3 M€).

To assess the economic attractiveness of the investment, the FR auction bid for having a NPV = 0 at the end of year 5 is calculated. As it can be seen from Table 6, a bid of 47.0 k€/MW/year allows recovering the investment in 5 years. The total yearly FR revenues are obtained by multiplying the qualified power by the awarded bid.

A schematic diagram of the cash flows is given in Figure 11. As shown, the CAPEX paid at year 0 give a largely negative actualized net cash flow (aNCF). Then, the cumulative aNCF (cumANCF in the figure) increases due to the net revenues coming from FR provision. At the end of year 5, the RV is considered and the final cumulative aNCF is 0 as the NPV.

As it has been shown, the long idle periods and the consequent large amount of energy withdrawn have a negative impact on economics and operations, thus justifying the adoption of a multiservice strategy to effectively exploit the battery when FR is not required.

3.2. Multiservice Study Case. In the multiservice case, BM participation is foreseen outside the FR availability blocks. This aims at increasing both economics and operational efficiency. In Figure 12, power and SoC profiles for the multiservice simulation are shown. The power profile is always dynamic, with very scarce idle intervals; indeed, BESS is participating to BM for the provision of RR when it is not available for FR. In particular, some short periods with larger power spikes can be recognized: these are the availability hours of FR. Instead, the remainder of the time is characterized by power set-points generally equal or lower than 1.5 MW: this is the RR provision. Given the fact it represents a constant power set-point for 1 or more hours (contracted on 4-hour market sessions) and considering an EPR of 0.5 hours, RR power is always limited.

This leads to a different SoC evolution too. The SoC profile gets spikier, but it hardly gets to saturation (100% or 0). This is because the implemented control strategy only bids the available energy content on BM: if the BESS is awarded, it is usually able to provide (for the whole contracted time) the awarded power, getting toward SoC limits without hitting them.

A zoom on some working hours is presented in Figure 13. Analyzing the mid chart, a time interval outside availability blocks can be seen. In that period, BESS participates to the BM and is accepted for the downward

TABLE 6: FR revenues requirement for having a NPV = 0 at year 5.

Key	Value	Unit
FR auction bid	47	k€/MW/y
Qualified power	8	MW
FR revenues	376	k€/y
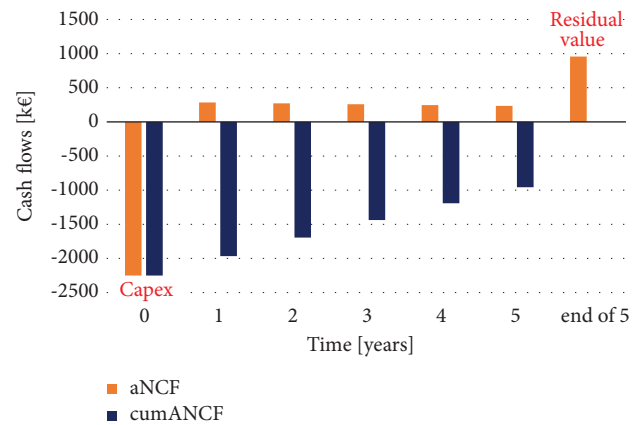
FIGURE 11: Actualized net cash flow of the investment with the targeted FR remuneration (NPV = 0 at year 5).

provision of RR for 4 consecutive hours, from 12 : 00 to 16 : 00, with a P_{RR} around 1 MW. The energy content increases by almost 4 MWh; therefore, SoC rises toward 100%. In the last 30 minutes of provision, the SoC gets above 96% and the capability chart limits the absorbed power: only 0.5 MW can be absorbed. All the requested power for RR in the limited period is considered as a nonperformance (NP) and is subject to a penalty.

At 4 PM, a buffer period occurs before the starting of the availability block. In this period, SoC is restored toward target SoC, having the battery, injecting power toward the grid (at 0 €/MWh). Even outside availability blocks, SoC management takes place only in case the frequency is within the dead band; otherwise it stops. Finally, at the end of the mid chart, the availability block starts. Some spikes followed by fade-out are shown due to over-frequency. When the frequency is within the dead band, still SoC management occurs (SoC is still around 60%).

A highlight on the BM performance and on the market model is given in the following. The BESS bids either upward or downward every hour, excepts for 1000 hours of availability for FR, and splits in 100 blocks and the 1-hour buffer
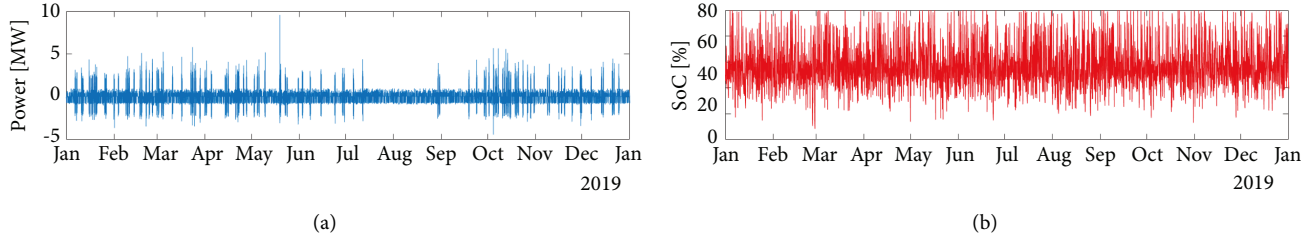
(a)

(b)

Figure 12: Power (a) and SoC (b) simulation results for multiservice case.
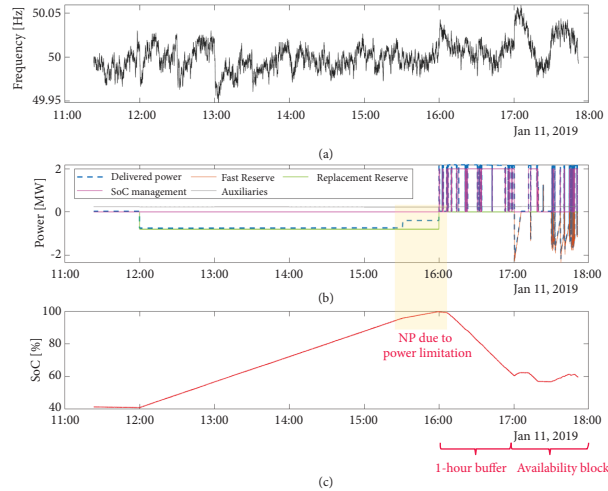

Figure 13: Detail on multiservice BESS management, including frequency variation (a), power management (b), and SoC evolution (c).

before each block. It is awarded for 1557 hours (20.3% of time) for upward provision and 1693 hours (22.1%) for downward provision: the overall award rate is 42.4%. This means that for the remainder (57.6% of time), the BESS offers at a price that is either higher than the upward maximum accepted on the market or lower than the downward minimum.

For what concerns the technical performances, Table 7 presents the yearly energy flows. The total energy cycled by the BESS is almost 3 times that of FR-only case, due to the large requested energy for RR provision. Thanks to the RR provision, BESS obtains a further revenue stream and drastically reduces the energy withdrawn. Indeed, the withdrawal is less than 30 MWh, decreasing by a factor 9 with respect to the previous case. The reliability in the provision of RR is high (98.2%): only 1.8% of requested energy is NP. The NP_{RR} depends on the limitations posed by the capability chart and by the maximum and minimum SoC thresholds. Because of the large increase in energy flows, BESS estimated lifetime is reduced to 7.8 years. On the contrary, BESS efficiency improves (83.6%), but it is still low since the RR provision usually requests power around 10–20% of the nominal power.

The main data for the economic evaluation are presented in Table 8. CAPEX and OPEX do not change, as well as the NPP_{FR}. New cash flows are added for what concerns the RR provision. The impact of BM participation is twofold: on the one hand, it adds some net revenues given by the algebraic

Table 7: Technical results from multiservice study case.

Key	Value	Unit
Total energy cycled	3200	MWh/y
FR requested	819	MWh/y
RR requested	2304	MWh/y
SoC management (charging)	112	MWh/y
SoC management (discharging)	97	MWh/y
Auxiliary demand	282	MWh/y
Energy withdrawal	29	MWh/y
NP_{FR}	0	%
NP_{RR}	1.8	%
BESS estimated life	7.8	years
Average efficiency	83.6	%

sum of revenues for upward provision (discharging), costs for downward provisions, and penalties for NP_{RR}; on the other hand, RR provision decreases the risk for the BESS energy content of being depleted outside the availability blocks, and therefore the energy withdrawal at bill cost. The first net revenue stream represents an additional yearly cash flow of around 80 k€. The avoided bill costs represent around 40 k€ of savings. Oppositely, BESS lifetime decrease implies a reduction by 1/3 of its residual value with respect to the FR-only case.

The opposite contribution of the additional revenue streams and the increased aging of the BESS lead to the FR auction bid presented in Table 9: the auction bid to have a

TABLE 8: Economic results for multiservice study case.

Key	Value	Unit
CAPEX (year 0)	−2250	k€
OPEX	−25	k€/y
NPP_{FR}	0	k€/y
RR revenues (upward provision)	88	k€/y
RR costs (downward provision)	−4	k€/y
NPP_{RR}	−4	k€/y
SoC management costs (charging)	−6.7	k€/y
SoC management revenues (discharging)	5.9	k€/y
Bill total cost	−5.8	k€/y
Residual value (end of year 5)	809	k€

TABLE 9: Multiservice revenue requirement for having a NPV = 0 at year 5.

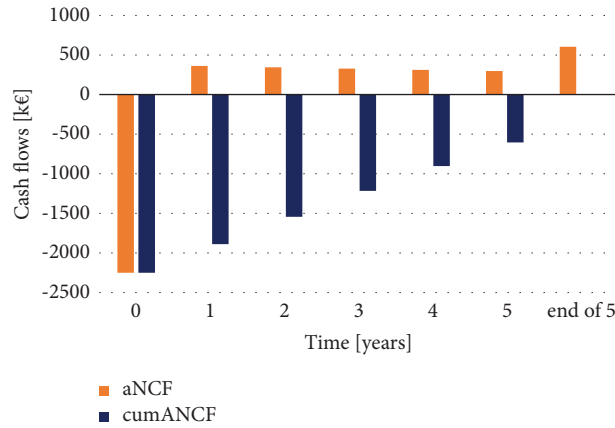| Key	Value	Unit
FR auction bid	41.5	k€/MW/y
Qualified power	8.0	MW
FR revenues	332	k€/y

FIGURE 14: Actualized net cash flow of the investment with the targeted multiservice remuneration (NPV = 0 at year 5).

null NPV at the end of year 5 is 41.5 k€/MW/year, meaning that either the marginal cost is 13% lower with respect to the FR-only case or the investment's internal rate of return (IRR) would rise from 5.0% (FR-only case) to 7.4%.

The cash flow for the multiservice strategy is presented in Figure 14. The same CAPEX apply, while from year 1 to 5 slightly higher aNCFs are able to recover steeply toward a null NPV. In any case, the lower residual value at the end of year 5 brings to 0 the NPV.

3.3. Sensitivity Analysis on the Efficient FR Auctioned Price. To better analyze the benefit of a multiservice strategy, the following sensitivity analysis is proposed. The IRR at the end of year 5 is proposed for different input parameters:

(i) an energy-based specific CAPEX (k_e) ranging from 200 to 500 k€/MWh;

(ii) a FR auction bid ranging from 20 to 70 k€/MW/year.

The results are shown in Figure 15. The multiservice approach allows a slight switch toward green, therefore toward larger IRR. This becomes more apparent for lower CAPEX: at CAPEX around 350–450 k€/MWh, the gap between the strategies in terms of IRR is around 0.2–1.6%, and then the distance increases for CAPEX lower than 300 k€/MWh (2.0–4.9%). This means that it will be more and more important to select the best BESS control strategy to improve economics with future BESS costs. Considering real awarded prices within FR auctions and expected CAPEX for FRU, a focus on the subset within the dashed area of Figure 15 is proposed. For bids around 30 k€/MW/year and CAPEX around 250–300 k€/MWh, the multiservice strategy makes the difference between a negative and a positive IRR. For instance, IRR equal to 2.0% is shown for multiservice case, considering 30 k€/MW/year and a low CAPEX of 250 k€/MWh. For the same values, the FR-only IRR is negative.

FAST RESERVE ONLY
CAPEX (k€/MWh)

		200	250	300	350	400	450	500
FR auction bid (k€/MW/y)	70	20.6%	16.8%	13.9%	11.5%	9.6%	8.0%	6.7%
	60	15.6%	12.4%	10.0%	8.1%	6.5%	5.2%	4.0%
	50	10.6%	8.1%	6.1%	4.6%	3.3%	2.3%	1.4%
	40	5.6%	3.8%	2.3%	1.2%	0.2%	-0.5%	-1.2%
	30	0.7%	-0.5%	-1.5%	-2.2%	-2.8%	-3.4%	-3.8%
	20	-4.1%	-4.7%	-5.2%	-5.6%	-5.9%	-6.1%	-6.3%

MULTISERVICE
CAPEX (k€/MWh)

		200	250	300	350	400	450	500
FR auction bid (k€/MW/y)	70	26.2%	21.2%	17.2%	14.0%	11.3%	9.1%	7.2%
	60	20.9%	16.4%	12.9%	10.1%	7.8%	5.9%	4.2%
	50	15.5%	11.7%	8.7%	6.2%	4.3%	2.6%	1.2%
	40	10.0%	6.8%	4.3%	2.4%	0.7%	-0.7%	-1.8%
	30	4.5%	2.0%	0.0%	-1.6%	-2.9%	-3.9%	-4.8%
	20	-1.1%	-2.9%	-4.4%	-5.5%	-6.4%	-7.2%	-7.9%

FIGURE 15: IRR sensitivity analysis with respect to BESS CAPEX estimation and FR bid price [€/MW/y].

4. Conclusion

A techno-economic analysis on the fast reserve pilot project in Italy has been proposed. The analysis takes advantage of a BESS model developed in Politecnico di Milano, able to test the performances of BESS operations on grid-connected configuration. The model has been improved and extended in the framework of this study, to be used on a very small EPR (e.g., 0.5 hours). The analysis compares a case study in which only fast reserve (FR) is provided and a multiservice case with a participation to balancing market (BM) for the provision of replacement reserve (RR), too. The multiservice strategy features the sequential provision of the two services: this is because FR remuneration is capacity-based and the economic attractiveness of that service is worth dedicating all the BESS capacity to it. For what concerns FR provision, real-world frequency data are sent as input to the models. For what concerns RR provision, it takes advantage of a simplified BM model based on statistical data of the Italian market that proposes the acceptance or rejection of the bid. The main added value of the proposed analysis consists in the integration of a comprehensive tool for the techno-economic assessment of asset operation within a data-driven market modeling. This is done including in the same work.

(i) an accurate and comprehensive BESS model,
(ii) a market model specifically developed on the national BM,
(iii) a detailed modeling of a fast frequency regulation service control strategy and of the BESS control management.

The outcome of the study consists in the evaluation of the optimal bidding strategy for Italian FR auctions as a function of BESS CAPEX.

The outcomes of the study show that the provision of ancillary services is always realized with a very high degree of reliability for both services, with 100% reliability for FR and 98.1% reliability for RR. The BESS performance, in terms of average efficiency, is generally low for the application foreseen. In FR-only case, this is due to the large time idle of the BESS (FR is only requested for 1000 hours a year). In multiservice case, the power requested for RR is usually low, and BESS effort is requested in an operating region where efficiencies are lower due to larger losses in power conversion systems. In any case, multiservice strategy improves the efficiency from around 75 to 84%. The economics improves for multiservice strategy, too. With the considered assumptions (FR auction bid to have a return on investment at the end of year 5), the IRR passes from 5.0% in the FR-only case to 7.4% in the multiservice strategy. A sensitivity analysis is then performed to check different auction bids and different CAPEX.

Results indicate that there is a net advantage in adopting a multiservice strategy for revenue stacking. Beyond the economic results shown in previous sections, some other elements can be highlighted:

(i) in case of a multiservice strategy, the withdrawn energy from the grid is drastically reduced; thus, the BESS needs fewer exchanges with the grid for SoC management and for its load. This is an advantage for both the grid operator and the users, and can fit with energy management strategies, for instance, in

the context of microgrids and smart energy districts [40];

(ii) considering recent prices (Q3-Q4 2021 and Q1 2022) in both DAM and ancillary services markets (ASM), the possible economic outcome of the multiservice strategy would be even more positive: indeed, both the avoided cost (related to DAM price) and the BM revenues (related to ASM prices) would have been larger and would have shown a larger gap with respect to FR-only case. These high prices are not considered in the simulations since they are not expected to remain in the long period [41];

(iii) the aging model considered estimates short BESS lifetime. This is because it considers both cycle and calendar aging: the latter is fixed and based on own elaboration from average data retrieved from [39]. Anyway, it is known that calendar aging highly depends on SoC operating conditions: it decreases faster in case of storage close to 100% of SoC, in particular for what concerns NMC cells [42]. The proposed application minimizes the time at very high SoC, thus decreasing the aging rates and increasing the BESS lifetime.

Finally, looking for future opportunities for BESS in Italy, the most promising options can be found in the pilot project for automatic frequency restoration reserve (aFRR) [43] and in general in the dispatch reform ongoing [44]; the proposed approach results to be a viable procedure to evaluate the technical and economic feasibility of those services.

Data Availability

All data used in the research are included in the article, with proper reference to their origin and residence.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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