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 multi-use, 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 ($P_{\text{quad}}$ in MW): a $P_{\text{quad}}$ 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 provision 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-issued 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 ($P_{\text{mgmt}}$); and the RR control block, whose output is the requested power for FR ($P_{\text{req}}$). The multiservice case also includes (in grey) the RR control, which returns the bid power for RR ($P_{\text{req}}$); 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 ($P_{\text{grid}}$) that is added to the auxiliary system power ($P_{\text{aux}}$) to give the power requested to the BESS ($P_{\text{req}}$), sent as input to the BESS.
Main outputs of the BESS model are the SoC, the BESS efficiency ($\eta_{\text{BESS}}$), 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 ($P_{\text{req}}$).

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);
(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 $P_{\text{qual}}$ 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

Table 1: BESS characteristics considered in the study case.

| Key                        | Value | Unit |
|----------------------------|-------|------|
| Nominal energy ($E_{\text{n}}$) | 5     | MWh  |
| Nominal power ($P_{\text{n}}$) | 10    | MW   |
| Qualified power ($P_{\text{qual}}$) | 8     | MW   |
| SoC management power ($P_{\text{mgmt}}$) | 2     | MW   |
| Target SoC (SoC-target) | 55%   | %    |

Figure 3: Surface representing BESS roundtrip efficiency.
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-
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.

\[
\text{SoC}_{\text{hi}} = \text{SoC}_{\text{max}} - P_{\text{qual}} \times \frac{15}{60} \times \frac{1}{E_{\text{r}}} \times \eta_{\text{avg}} = 63.2\%,
\]

\[
\text{SoC}_{\text{lo}} = \text{SoC}_{\text{min}} + P_{\text{qual}} \times \frac{15}{60} \times \frac{1}{E_{\text{r}}} \times \frac{1}{\eta_{\text{avg}}} = 43.5%,
\]

where SoC max is 100%, SoC min is 0%, and \(\eta_{\text{avg}}\) 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

Table 2: Fast reserve requirements influencing BESS dynamic response.

| Key                         | Value          | Notes                                      |
|-----------------------------|----------------|--------------------------------------------|
| Dead band (level #1)        | ±20 MHz        |                                            |
| Full activation (level SAT) | ±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. |

Algorithm 2: FR availability block selection.
beginning of each availability block and deactivates at its end: this 1-hour advance allows to restore the SoC to SoC\(_\text{target}\) 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 least 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 holidays) 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\(_\text{target}\), the offered price for upward regulation decreases proportionally to the distance of SoC\(_t\) from SoC\(_\text{target}\), thus increasing the probability of acceptance;

(ii) for the same reason, if SoC\(_t\) is lower than SoC\(_\text{target}\), the price offered for downward regulation increases proportionally to the distance of SoC\(_t\) from SoC\(_\text{target}\).

The bidding strategy for hour \(h\) is implemented as in

\[
B(h) = \mu(h) - \sigma(h) * \frac{\text{SoC}(t) - \text{SoC}_{\text{target}}}{100}.
\]

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 reserves 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\(_\text{target}\) only upward (discharge) service is offered and vice versa.

Focusing on the Italian scenario, RR product is traded on market sessions of 4 hours (\(t_{\text{mkt}}\)). 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 \(k_{\text{mkt}}\) is a parameter inducing a safety margin on the definition of \(P_{\text{RR}}\) (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, \(P_{\text{RR}}\) 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
power set-point. The requested power \((P_{\text{req}})\) can be formulated as

\[
P_{\text{req}} = P_{\text{grid}} + P_{\text{mgmt}} + P_{\text{aux}},
\]

where \(P_{\text{grid}}\) is the power for the provision of grid services, summing the power for FR \((P_{\text{FRU}})\) and RR \((P_{\text{RR}})\), \(P_{\text{mgmt}}\) is the power for SoC management, and \(P_{\text{aux}}\) 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 con-
sidered are compared in terms of energy exchanged, tech-
nical 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 avail-
ability 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 (\( P_{moni} \)) 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 with-
drawal (\( P_{with} \)) 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 perfor-
mances increase when the withdrawal is reduced
through the provision of downward power regula-
tion.

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

\[
\begin{align*}
P_{NP,FRU} &= P_{FRU} & \text{if } \frac{|P_{req} - P_{del}|}{P_{req}} > 5\%, \\
&= 0 & \text{elsewhere},
\end{align*}
\]

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 \( P_{NP,RR} \). 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 \( P_{NP,FRU} \) and \( P_{NP,RR} \)
results in the NP-related energy for the two services (\( E_{NP,FR} \)
and \( E_{NP,RR} \)). The NP share (\( P_{NP,FRU} \) and \( P_{NP,RR} \)) 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. Gen-
erally, a NP below 5% is welcomed [32]. Efficiency is esti-
mated 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:

\[
\text{CAPEX} = k_e \cdot E_n + (P_n - E_n) \cdot k_p, \quad (5)
\]

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 \( E_n \)
\((E/P \text{ lower than 1, higher c-rates requested})\) 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 re-
mainder, 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).

\[
NPV = CAPEX + \sum_{t=0}^{N} \frac{NCF_t}{(1 + r)^t} + \frac{RV}{(1 + r)^N} = 0, \tag{6}
\]

\[
NCF = R_{FR} + R_{BM} + R_{dis} - C_{ch} - C_{bill} - NPP_{FR} - NPP_{BM}, \tag{7}
\]

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

\[
RV = CAPEX \times \frac{(t_{EoL} - t)}{t_{EoL}}, \tag{8}
\]

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 \(\pm 150\) 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: \(\Delta f\) 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 \(\pm 2\)±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 \(N_{FR}\), 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
| 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€/MWh/year   |           |
| DAM price                                 | 60     | €/MWh         | [36]      |
| Bill cost                                 | 200    | €/MWh         |           |
| Injection price                           | 0      | €/MWh         |           |
| FR revenues ($R_{FR}$)                    | Based on auctioned bid | k€/MW/year |           |
| BM revenues ($R_{BM}$)                    | Based on market model | k€/MW     |           |
| Fee on FR nonperformance                  | % of capacity-based payment | k€/MW/year | [10]     |
| Fee on BM nonperformance                  | 100    | €/MWh         | [34]      |
| Actualization rate®                       | 5      | %             |           |

![Figure 9: Power (a) and SoC (b) simulation results for FR-only case.](image)

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

| 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         |
| NPVR                                      | 0      | %             |
| BESS estimated life                       | 11.6   | years         |
| Average efficiency                        | 75.1   | %             |
therefore 47.5 k€. There is no penalty for NP\textsubscript{FR}, since there is no NP\textsubscript{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 \textless{} 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 provision of RR for 4 consecutive hours, from 12:00 to 16:00, with a $P_{\text{RR}}$ 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.
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 NP_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 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
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.
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

![Figure 15: IRR sensitivity analysis with respect to BESS CAPEX estimation and FR bid price [€/MW/y].](image-url)
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.

References
[1] T. Bossmann, P. Barberi, and L. Fournié, "Effect of high shares of renewables on power systems," METIS Studies, pp. 1–34, EU Commission, Brussel, Belgium, 2018.
[2] G. Rancilio, A. Rossi, D. Falabretti, A. Galliani, and M. Merlo, “Ancillary services markets in europe: evolution and regulatory trade-offs,” Renewable and Sustainable Energy Reviews, vol. 154, Article ID 111850, 2022.
[3] IRENA, Innovation Landscape Brief: Innovative Ancillary Services, IRENA, Abu Dhabi, UAE, 2019.
[4] D. M. Greenwood, K. Y. Lim, C. Patios, P. F. Lyons, Y. S. Lim, and P. C. Taylor, “Frequency response services designed for energy storage,” Applied Energy, vol. 203, pp. 115–127, 2017.
[5] B. K. Poolla, D. Groß, and F. Dörfler, “Placement and implementation of grid-forming and grid-following virtual inertia and fast frequency response,” IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 3035–3046, 2019.
[6] IRENA, Electricity Storage and Renewables: Costs and Markets to 2030, IRENA, Abu Dhabi, UAE, 2017.
[7] H. Chen, S. Baker, S. Benner, A. Berner, and J. Liu, “PJM integrates energy storage: their technologies and wholesale products,” IEEE Power and Energy Magazine, vol. 15, no. 5, pp. 59–67, Sep.
[8] T. Thiend, C. Schweer, D. V. Stein, A. Moser, and D. U. Sauer, “Real-world operating strategy and sensitivity analysis of frequency containment reserve provision with battery energy storage systems in the German market,” Journal of Energy Storage, vol. 13, pp. 143–163, 2017.
[9] National Grid, Future of Balancing Services, National Grid, Warwick, UK, 2017.
[10] Terna, Accompanying Note on Fast Reserve Public Consultation, Terna, Rome, Italy, 2019.
[11] F. V. Julich, “Comparison of electricity storage options using levelized cost of storage (LCOS) method,” Applied Energy, vol. 183, pp. 1594–1606, 2016.
[12] NREL, Cost Projections for Utility-Scale Battery Storage: 2021 Update, NREL, Golden, CO, USA, 2021.
[13] T. A. Nguyen, D. A. Copp, and R. H. Byrne, “Stacking revenue from energy storage providing resilience, TD deferral and arbitrage,” in Proceedings of the IEEE Power and Energy Society General Meeting, Atlanta, GA, USA, August 2019.
[14] F. Braeuer, J. Rominger, R. McKenna, and W. Fichtner, “Battery storage systems: an economic model-based analysis of parallel revenue streams and general implications for industry,” Applied Energy, vol. 239, pp. 1424–1440, 2019.
[15] S. Engberger, A. Jossen, and H. Hesse, “Unlocking the potential of battery storage with the dynamic stacking of multiple applications,” Cell Reports Physical Science, vol. 1, no. 11, p. 100238, 2020.
[16] P. V. Brogan, R. Best, J. Morrow, R. Duncan, and M. Kubik, “Stacking battery energy storage revenues with enhanced service provision,” IET Smart Grid, vol. 3, no. 4, pp. 520–529, Aug. 2020.
[17] M. K. Metwaly and J. Teh, “Probabilistic peak demand matching by battery energy storage alongside dynamic thermal ratings and demand response for enhanced network reliability,” IEEE Access, vol. 8, pp. 181547–181559, 2020.
[18] C. M. Lai and J. Teh, “Network topology optimisation based on dynamic thermal rating and battery storage systems for improved wind penetration and reliability,” Applied Energy, vol. 305, p. 117837, 2022.
[19] F. Mohamad, J. Teh, and C. M. Lai, “Optimum allocation of battery energy storage systems for power grid enhanced with solar energy,” Energy, vol. 223, Article ID 120105, 2021.
[20] H. Ahmad, A. Ahmad, and S. Ahmad, “Efficient energy management in a microgrid,” in Proceedings of the 4th International Conference on Power Generation Systems and Renewable Energy Technologies, Islamabad, Pakistan, April 2019.
[21] Y. Tian, A. Bera, M. Benidris, and J. Mitra, “Stacked revenue and technical benefits of a grid-connected energy storage system,” IEEE Transactions on Industry Applications, vol. 54, no. 4, pp. 3034–3043, 2018.
[22] G. B. M. A. Litijens, E. Worrell, and W. G. J. H. M. van Sark, “Economic benefits of combining self-consumption enhancement with frequency restoration reserves provision by photovoltaic-battery systems,” Applied Energy, vol. 223, pp. 172–187, 2018.
[23] European Commission, Commission Regulation (EU) 2017/2195 Establishing a Guideline on the Electricity Balancing, European Commission, Brussels, Belgium, 2017.
[24] ARERA, Delibera 05 Maggio 2017—300/2017/R/rel, ARERA, Milan, Italy, 2017.
[25] F. Bovera, A. Blaco, G. Rancilio, and M. Delfanti, “Assessing the accuracy of different machine learning classification algorithms in forecasting results of Italian ancillary services market,” in Proceedings of the 2019 16th International Conference on the European Energy Market (EEM), pp. 1–5, Ljubljana, Slovenia, 2019.

[26] G. Rancilio, A. Lucas, E. Kotsakis et al., “Modeling a large-scale battery energy storage system for power grid application analysis,” Energies, vol. 12, p. 3312, 2019.

[27] G. Rancilio, A. Rossi, C. di Proio, M. Alborghetti, A. Galliani, and M. Merlo, “Grid-scale BESS for ancillary services provision: SoC restoration strategies,” Applied Sciences, vol. 10, no. 12, p. 4121, 2020.

[28] Gestore Mercati Energetici, Mercato Elettrico a Pronti (MPE), Gestore Mercati Energetici, Rome Italy, 2019.

[29] G. Rancilio, M. Merlo, A. Lucas, E. Kotsakis, and M. Delfanti, "BESS modeling: investigating the role of auxiliary system consumption in efficiency derating," in Proceedings of the 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), pp. 189–194, Sorrento, Italy, June 2020.

[30] Terna, Allegato 2 Regolamento Fast Reserve Requisiti Tecnici Dei Dispositivi Inclusi in Fast Reserve Unit, Terna, Rome, Italy, 2019.

[31] ARERA, Delibera 109/2021/R/eel, ARERA, Milan, Italy, 2021.

[32] Terna, Regolamento Fast Reserve, Terna, Rome, Italy, 2019.

[33] Pacific Northwest National Laboratory, Energy Storage Technology and Cost Characterization Report, Pacific Northwest National Laboratory, Richland, WA, USA, 2019.

[34] Terna, Rapporto Mensile Sul Sistema Elettrico - Dicembre 2019, Terna, Rome, Italy, 2020.

[35] WSP UK Ltd, Making Batteries Work, WSP UK Ltd, London, UK, 2020.

[36] GME, Relazione Annuale 2019, GME, Rome, Italy, 2020.

[37] ARERA, Relazione Annuale 2019, ARERA, Milan, Italy, 2019.

[38] M. Moncecchi, C. Brivio, S. Mandelli, and M. Merlo, "Battery energy storage systems in microgrids: modeling and design criteria,” Energies, vol. 13, no. 8, p. 2006, 2020.

[39] S. Grolleau, A. Delaille, H. Gualouset al., "Calendar aging of commercial graphite/LiFePO4 cell–predicting capacity fade under time dependent storage conditions,” Journal of Power Sources, vol. 255, pp. 450–458, 2014.

[40] E. González-Romera, M. Ruiz-Cortes, M. Milanes-Montero et al., “Advantages of minimizing energy exchange instead of energy cost in prosumer microgrids,” Energies, vol. 12, no. 4, p. 719, 2019.

[41] ACER, ACER’s Preliminary Assessment of Europe’s High Energy Prices and the Current Wholesale Electricity Market Design, ACER, Brussels, Belgium, 2021.

[42] P. Keil, SF. Schuster, J. Wilhelm et al., “Calendar aging of lithium-ion batteries,” Journal of the Electrochemical Society, vol. 163, no. 9, pp. A1872–A1880, 2016.

[43] ARERA, Delibera 25 Maggio 2021 215/2021/R/eel, ARERA, Milan, Italy, 2021.

[44] ARERA, Documento per la Consultazione 322/2019/R/eel, ARERA, Milan, Italy, 2019.