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BESS and the ancillary services markets: A symbiosis yet? Impact of market design on performance

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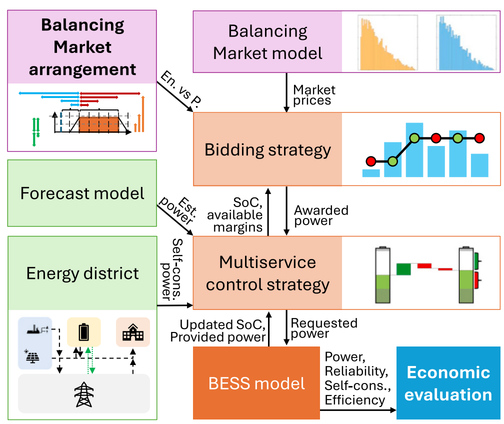
HIGHLIGHTS

- A comprehensive modelling suite modelling BESS vs balancing market compatibility.
- Testing regulatory barriers: symmetry, gate closure timing, dynamic services.
- Asymmetric provision of services widely improves reliability and economics.
- Revenue stacking: more self-consumption (+10%) in synergy with ancillary services.
- Dynamic services require short distance to delivery and allow larger delivery period.

GRAPHICAL ABSTRACT



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ABSTRACT

The evolution of ancillary services markets (ASM) and balancing products is ongoing. The aim of the evolution is to integrate the products over the national boundaries and to open the ASM to distributed energy resources (DERs). Among DERs, battery energy storage systems (BESS) are increasing their importance. In this work, we investigate by means of numerical simulations the effect of different evolutions in the regulatory framework on the performance of a BESS providing ancillary services. The analyzed regulatory barriers are selected based on ongoing evolution in EU market design. The following parameters are involved: power vs energy-intensive

Abbreviations: ACE, Area Control Error; aFRR, automatic Frequency Restoration Reserve; ASM, Ancillary Services Market; AUX, Auxiliaries; BESS, Battery Energy Storage System; BM, Balancing Market; BtM, Behind-the-Meter; CHP, Cogenerative Heat and Power plant; DAM, Day-Ahead Market; DER, Distributed Energy Resource; DtD, Distance to Delivery; E/P, Energy-to-Power ratio; EBGL, Electricity Balancing Guidelines; En, Nominal Energy; ESS, Energy Storage System; EU, European Union; FtM, Front-of-the-Meter; FRCE, Frequency Restoration Control Error; GCT, Gate Closure Time; HVAC, Heating Ventilation Air Conditioning; IM, Intraday Market; KPI, Key Performance Indicator; kW, kilowatt; MAE, Mean Absolute Error; mFRR, manual Frequency Restoration Reserve; MW, Megawatt; MWh, Megawatt-hour; NP, Nonprovision; NPP, Nonprovision penalty; Pn, Nominal Power; PV, Photovoltaic; qty, quantity; REF, Reference; RES, Renewable Energy Sources; RMSE, Root Mean Squared Error; RR, Replacement Reserve; SC, Self-consumption; SCADA, Supervisory Control And Data Acquisition; SoC, State-of-Charge; TD, Time Definition; TERRE, Trans European Replacement Reserves Exchange; TIDE, Testo Integrato del Dispacciamento Elettrico; TSO, Transmission System Operator; US, United States; η_{BESS}, BESS efficiency.

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services, symmetry of procurement, time definition and distance to delivery. The considered case study is a BESS associated to a large-scale energy district including load, a cogeneration plant, and a PV plant. Results are given in terms of energy flows, economics, operational efficiency, and reliability of service provision. Where both reliability, provision of large flexibility volumes, and good economic performance are achieved, we say that there is a symbiosis between BESS and the markets. This way, the best ASM arrangements abating regulatory barriers for BESS are defined.

1. Introduction

While many power systems are committed to increase (and rapidly increasing) the renewable energy sources (RES) penetration in the generation mix [1], some studies and evidence show that a larger RES penetration could increase electricity balancing costs [2–4]. In case the rise of RES is supported by improvements in balancing mechanisms, markets and technologies, the cost enhancement will likely be mitigated [5–7].

Programmable, non-fossil, flexible technologies such as energy storage systems (ESS) are considered among the key enablers for reaching high (to 100%) RES penetration [8]. Indeed, they can grant flexibility and balancing for the system via the provision of ancillary services. Ancillary services and ancillary services markets (ASM), originally built for conventional large-scale generation, should undergo a regulatory review to allow efficient and effective participation of distributed energy resources (DERs), including ESS [9,10]. In other words, regulation should be able to abate regulatory barriers [11]. When, indeed, the ESS are given the possibility to effectively provide ancillary services, they see the ASM as the core business [12], hence they are interested in offering flexibility at a competitive price, eventually lowering the system prices [13].

The research so far investigated regulatory barriers on electricity markets in different ways. Some studies [11,14] have highlighted the nature of regulatory barriers: they are not always explicit obstacles to the deployment of a technology or prohibition to enter a market. Instead, they can rely on a missing definition, on disregarding of a peculiarity of a technology, on the impossibility of capturing different revenue streams. Regulatory barriers have been categorized [15], and systematic reviews have been performed to understand which of the best trends are to follow [10]. The best practices have been highlighted and the possible lessons have been gathered [9,16,17]. Previous studies have generally proposed qualitative assessment of the impact of an ASM redesign. Some studies have proposed model-based quantitative analysis of the impact of ASM or Balancing Market (BM) redesign on the techno-economic performance of new resources. These studies focus on a limited set of parameters [18,19], generally including or focusing on the pricing rules [20,21]. Other studies are constrained by the existing rules and services, hence they focus more on the best control strategies for existing market layouts or on a comparison between them [22–27], rather than market design evolution. Few propose as a result a grid code reform [28]. In the found studies, no more than two parameters are considered and there is not a wide sensitivity analysis on them. In general, a comprehensive and quantitative analysis assessing the compatibility of new resources with the wide range of possibilities for balancing products and markets redesign is missing. In fact, usually studies focus on the impact that BESS can have on the grid [28–30], but less on the impact that a system reform can have on BESS performance.

BESS modelling-wise, several studies are available. In the past, models were focused on the battery and the cell, modelling the electrochemical section with high accuracy [31]. For utility-scale BESS, it gets clearer and clearer that studies on the techno-economic performance of a storage system must relate with operation and existing applications [32]. Recently, operational models are proposed encompassing the whole BESS and featuring a trade-off between accuracy and computational effort, thus allowing simulations on the mid to long period and on different applications [33,34]. Among these studies, several show that the battery is not the main source of losses in a BESS and highlight the weight of heating and cooling on plant energy losses/inefficiencies [35–37]. A model for analysing grid-connected, large-scale BESS is proposed in [38], featuring battery performance, power conversion system and auxiliary system to return BESS efficiency in market operation.

The aim of this work is quantitatively analysing the issue of ESS vs ASM compatibility, focusing on battery ESS (BESS) and modularly investigating the possibilities for redesigning balancing products. A set of simulations are performed to assess the provision of standard balancing products (thus compatible with the EU framework [39]) in different market designs by an energy district including BESS and RES. Results are given in terms of reliability of provision, effectiveness of provision (how much flexibility is provided), energy efficiency during the provision, and compatibility with behind-the-meter (BtM) services (i.e., Multiservice perspective). These quantities are then considered as aggregate to check whether there is overall economic convenience in the provision and to compare different market arrangements. Finally, to check that the proposed framework suits the analysis of real-world markets, the proposed methodology is adopted to investigate some country-specific examples of market redesign that occurred in recent years (e.g., automatic Frequency Restoration Reserve's auction scheme in Germany and balancing market reform in Italy).

The novelty of this work is proposing a modular approach in a quantitative analysis of ESS performance on ASM. This means analysing the effect of each market parameter on techno-economic performances, considering different parameters and a sound range for each of them. This allows to extensively analyze the redesign of standard balancing products. The outcomes include the overall economic evaluation of each BESS/ASM arrangement, as well as a cross comparison of specific performances, e.g., the amount of offered flexibility, the reliability of the provision, the operational BESS efficiency in each framework. The modular approach avoids binding the analysis to an existent regulatory framework. The adoption of standard balancing product can extend the validity of the results to the EU framework. The use of a multiparameter BESS model allows to consider all the main sources of inefficiency. Therefore, the work could be useful for guiding policymaking and regulatory choices while pursuing win-win arrangements for the participation of ESS to electricity balancing. Indeed, simultaneously assessing balancing services provision by the perspectives of efficiency, effectiveness, reliability, and compatibility with other services, the outcomes of the study highlight the arrangements able to gather high-level flexibility at a competitive cost.

The reminder of the paper is structured as follows. Chapter 2 details the methodology, including the market model, BESS model and control strategy for provision of ancillary services. Chapter 3 presents the case study and the layout of the simulation campaign. Chapter 4 provides techno-economic results and possible applications to evaluate real-world frameworks. Chapter 5 summarizes conclusions and policy implications.

2. Methodology

Being this work characterized by several blocks and routines, a summary of the proposed methodology is given here, including the rationale and the relation between each part (see Fig. 1), while each block is then better detailed in the following paragraphs.

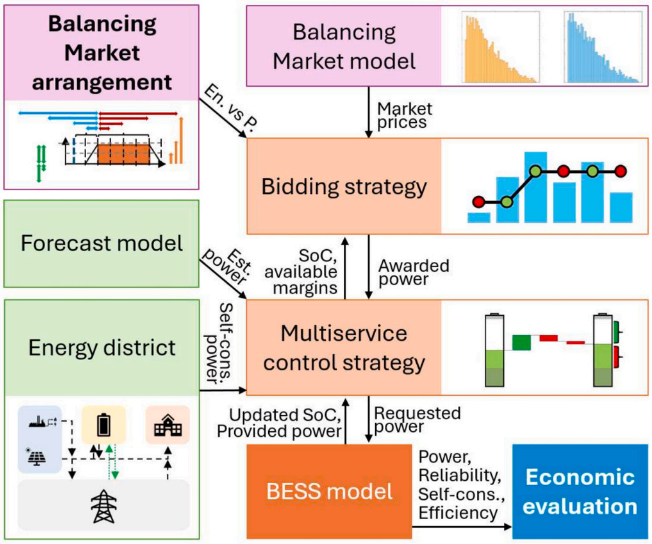


Fig. 1. The block diagram for the methodology of the study, with a detail of the adopted models and their input and output.

As described in the Introduction, the literature lacks a clear identification of the optimal market arrangements for the inclusion of BESS (especially integrated with RES) in ASM and for exploiting the flexibility that can be guaranteed by these fast and precise inverter-based resources. This identification of an optimal regulatory framework, to be reliable, should be supported by quantitative analyses and evidence. A systematic review of the market structure, of the proposed services and of the traded products is already present in the literature [10], highlighting the possible evolutions to be prioritized in a qualitative way.

The goal of this work is proposing a quantitative study to better and more specifically address the integration of ESS, specifically BESS, in the markets. To assess quantitatively the regulatory barriers and check how much they can limit the battery business, a modular analysis is proposed. It aims to depict a standard framework for real-world ASM: this is to produce results that apply to real contexts, yet generalizable at least to EU. The considered features are clearly defined in art. 24 and 25 of the Electricity Balancing Guidelines (EBGL [39]): a set of parameters that are common to many products and that can be modified by the regulation while redesigning them. A subset of these parameters is modified in a range to propose the modular sensitivity analysis subject of this study. The analyzed barriers are listed in paragraph 2.1.

Two standard balancing products are tested over a serial campaign of simulations, relaxing one by one the constraints in their provision that can represent a barrier. Standard balancing products are proposed by EU regulation (in alternative to specific products) to harmonize at a continental level the provision of frequency regulation (i.e., electricity balancing). The considered products are selected since they feature different characteristics in terms of dynamics, aleatory behavior, and energy-intensity. They are presented in paragraph 2.2. Namely, these products are automatic Frequency Restoration Reserve (aFRR) and Replacement Reserve (RR) characterized using historical data [40]. In particular, the aFRR represents a power-intensive and dynamic service, controlled by an input signal variable with Frequency Restoration Control Error (FRCE). In this study, it is aimed to represent frequency response services. Oppositely, RR is an energy-intensive, static service, aimed to represent power reserve. It requires a constant power setpoint for providers. Italian data are used as input of the simulation, but the use of standard products guarantees results that can be extended to EU. The same would not be possible in the case of testing a specific product (e.g., Fast Frequency Response) [39].

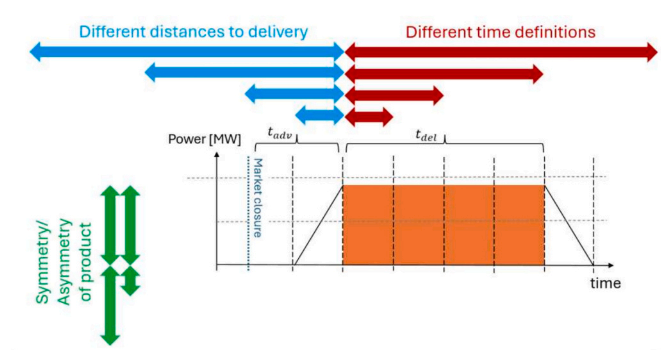
The considered plant layout is the energy district whose working principles are described in paragraph 2.5.3, where the integrated BESS works as an enabler of ASM for RES and DERs. The outcomes return the acceptable (or optimal) ranges of the analyzed parameters for the integration market/BESS. As described in paragraph 2.3, a detailed BESS model featuring multiparameter and variable efficiency is adopted to improve the reliability of the results. The BESS model is adapted from study [38], and it is used to test a month of ASM participation adopting the Multiservice Strategy proposed in [41] for residential BESS, here reworked to suit the energy district and described in paragraph 2.5. Thus, the BESS is operated to provide behind-the-meter (BtM) and front-of-the-meter (FtM) services in the energy district. FtM services are based on the balancing market model illustrated in paragraph 2.4.

The results are analyzed considering several techno economic KPIs (presented in paragraph 2.6) to check the performance of the BESS and its possible correlation with the value of tested parameters. In case correlations are found, the optimal values of each parameter for enhancing BESS performance are recognized as the range where they return effectiveness, efficiency, reliability, and compatibility with other services above a threshold.

2.1. The balancing market arrangements and the analyzed barriers

As said, standard balancing products are characterized by a set of parameters. The study varies a set of these parameters in a range of interests how BESS performance in providing the service is affected. The tested parameters are presented in Fig. 2. The parameter selection has been performed starting with the suggested redesign options highlighted by the analysis presented in [10], selecting those parameters that directly impact the control strategy and the bid volumes.

1. The symmetry/asymmetry of products is considered in the study. Symmetry refers to the constraint of offering the same amount of upward and downward regulation. Asymmetry relaxes the constraint, e.g.: a resource can offer 1 MW upward and a different quantity downward (even 0). The aFRR and RR are proposed in the study in both configurations. In actual implementations, the balancing products are present both ways: Frequency Containment Reserve (FCR) is generally symmetric, but for Greece and Ireland; manual Frequency Restoration Reserve (mFRR) is generally asymmetric; both configurations are diffused for aFRR and RR [42].
2. Electricity balancing is generally pursuing a review of the services. Faster services are proposed, or more power-intensive ones, to meet the needs of the system and the peculiarities of new resources [43]. The services review is partially considered comparing two different standard products with opposed features: aFRR is power-intensive, generally characterized by a spiky power request profile (see



	Tested values
Services	aFRR – RR
Symmetry	No – Yes
Time definition (h)	1, 2, 4, 8, 24
Distance to delivery (h)	0, 0.5, 1, 4, 24

Fig. 2. The framework of the standard balancing product with a highlight on the tested parameters.

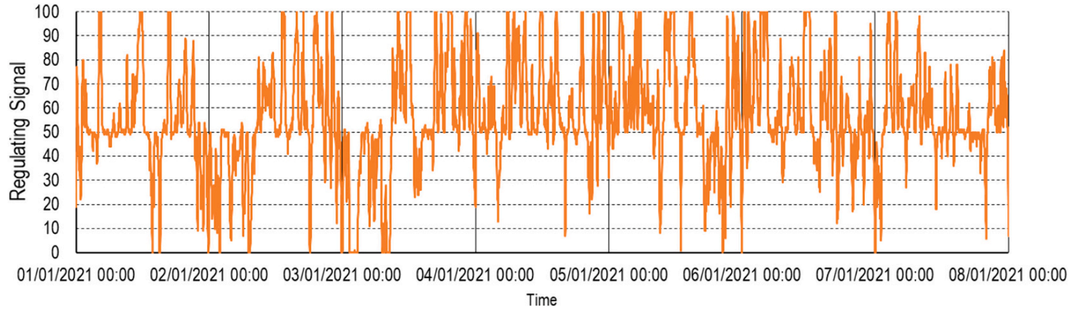


Fig. 3. Regulating Signal for aFRR in the Italian peninsula for the first week of 2021 [40].

Fig. 3) often changing power flow direction (withdrawing/injecting); RR is energy-intensive, usually characterized by a constant power request for the contracted time slot.

3. Time definition could define the minimum delivery time for a service or the duration of a market session (i.e., the distance between two market gate closures for the same product). In this case, the latter definition is adopted. This is to assess the impact of increasing the market session on limited energy resources: in principle, more sessions (i.e., lower time definition) could indicate less energy requests for the same bid power. The variation in the time definition of the products is tested by the study as depicted in Fig. 2. Shorter or longer time definitions are considered in the simulations. This is implemented via different market session durations (t_{mkt}).
4. The time between market gate closure and the beginning of the delivery time is often referred to as distance to delivery. It indicates how in advance a bid must be submitted to the market. Electricity markets are usually moving to occur closer to real time, both for what concerns ASM and intraday markets (IM) [44,45]. In any case, still many services are contracted a day/a week in advance [23]. Different distances to delivery are tested. This means, different time advances (t_{adv}) for estimating and bidding the flexibility.

The set of previously listed parameters/features is considered comprehensive of the evolutions of ASMs that should be more carefully analyzed and prioritized, also based on [10].

2.2. The provided ancillary services

The BESS is tested on the provision of two different standard balancing products based on the Italian data and framework. The first is aFRR: it is activated after the FCR with the aim of restoring the nominal frequency value (i.e., 50 Hz in Europe). In Italy, taken as model for the service definition, it is activated on 1-min setpoints according to the *Segnale di Livello*: it is a proportional-integral control considering as input FRCE (former ACE), correlated to frequency deviation [46]. AFRR requires a bid quantity each hour for upward and downward ($P_{bidUp}(h)$ and $P_{bidDn}(h)$). If awarded, the interval [-$P_{bidDn}(h)$, $P_{bidUp}(h)$] becomes the range for the setpoints related to the provision of the service, that superimposes to the exchange schedule of the resource with the grid. The *Segnale di Livello* or Regulating Signal (S) ranges from 0 to 100. The power to be provided each minute is defined by the following equation.

$$\begin{cases} P_{ASM}(t) = P_{bidUp}(t)*\dfrac{S-50}{50} \ \ if\ S \geq 50 \\ P_{ASM}(t) = P_{bidDn}(t)*\dfrac{S-50}{50} \ \ if\ S < 50 \end{cases} \tag{2.1}$$

Therefore, upward service must be provided when $S > 50$, elsewhere the downward provision is requested. Full $P_{bidUp}(h)$ is delivered when $S = 100$; no power is delivered if $S = 50$; the full $P_{bidDn}(h)$ is absorbed with $S = 0$. A statistical study shows that S variability is limited in a minute-period (i.e., the next value is in the neighborhood of the previous one), so that a limited ramp is requested to the resources each minute. S valid for the first week of 2021, used in the study, is presented in Fig. 3. It is worth noting that, as of 2023, the regulating band of aFRR in Italy is symmetric: each resource is awarded of a $P_{bidUp}(h) = P_{bidDn}(h)$. In any case, eq. (2.1) works for both symmetric and asymmetric provision, thus allowing generalization.

The second considered ancillary service is the RR. It requests a constant power setpoint for the contracted period (e.g., 1 h), coherent with the bid quantity. Clearly, asymmetric regulating band provision is requested (i.e., the resource can offer both upward and downward and it can be awarded in either the direction or none).

Fig. 4 represents some hours of aFRR and RR provision. In both cases, the resource bids a quantity (dashed lines) for upward and a quantity for downward provision. In case the bid is awarded (shaded areas), the resource must provide the requested power (solid line). For RR, the power is constant, only depending on the awarded bid quantity. For aFRR, the requested power varies each minute based on the bid quantity and on the Regulating Signal. In the figure, asymmetric provision is depicted. The bid power for each service is defined by the control strategy as in paragraph 0.

It is worth stressing that, even if the modelling is based on Italian ancillary services, the two presented services are archetypes of standard products available in most of EU markets. E.g., the aFRR is based on FRCE, computed similarly all over EU and in US, too [47]. Instead, RR is a reserve provision with a constant setpoint requested on an hourly (or quarter-hourly) basis, it is now traded at EU level by means of the TERRE international platform [48].

2.3. The BESS modelling

In this multifaceted system, the technological modelling of the BESS is addressed by adopting an updated version of [38]. It is a multiparameter empirical model suitable for large-scale grid-connected BESS, assessing the performance of the battery, the power conversion system and the auxiliary systems. It has been validated by comparing the outcomes with a real system providing frequency regulation. It requires as input a set of variables, i.e., the requested power to BESS ($P_{req}(t)$), a feedback on the BESS SoC ($SoC(t-1)$), and the ambient temperature. It delivers as output the actual power delivered by the BESS ($P_{del}(t)$), its efficiency, and its SoC evolution ($SoC(t)$). It features a variable efficiency with respect to requested power and SoC. It features a capability curve that limits the maximum available power with respect to SoC (i.e., charge power is limited at very high SoC and discharge power at very low SoC). It features auxiliary systems to replicate the ones of a mid-to-large-scale BESS (e.g., HVAC, fans, fire alarm, SCADA, etc.), with an electricity demand variable with ambient temperature and power requested to BESS [36]. The model offers a trade-off between accuracy and computational time. Thus, it suits a study that requires a set of simulations (i.e., tens of simulations) for a long period (i.e., a monthly period).

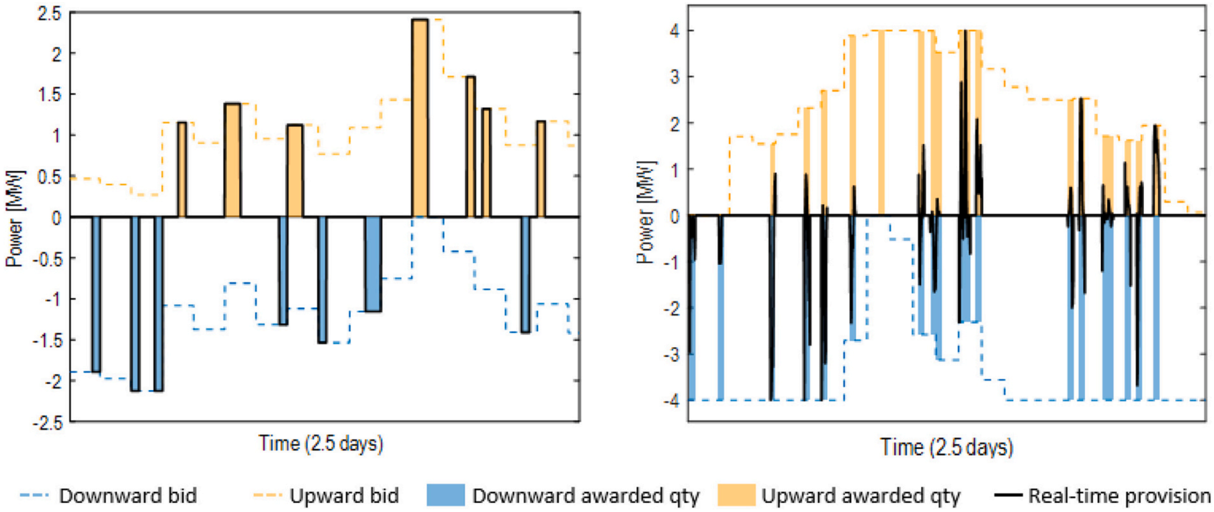


Fig. 4. A sample of the provision of aFRR (left) and RR (right), upward (orange) and downward (blue). The dashed lines depict the bid quantities, the shaded areas represent the awarded bids, the black line is the power requested in the real-time provision.

2.4. The balancing market modelling

A simplified BM model is implemented with the aim of defining if each bid is awarded. A maximum accepted price for upward reserve and a minimum accepted downward price are defined for each hour: these represent the marginal prices for the market. They are estimated based on a statistical analysis of the Italian ASM, performed on BM data for the period 2017–2019, to have prices for a business-as-usual situation (i.e., before Covid-19 and war in Ukraine). These marginal prices are the less convenient (from the system perspective) prices that are awarded on the market for a specific market session. The average marginal prices and standard deviations coming from the statistical analysis of BM are adopted to define a normal distribution of the hourly marginal awarded prices for each regulation, for both working days (Monday to Friday) and holidays (Saturdays, Sundays and bank holidays). Then, these outcomes are elaborated to feed the model with a random hourly value coming from the probability distribution for that hour of the day. The distribution of the marginal prices fed to the model is reported in Fig. 5. The probability distributions have been cut to avoid unrealistic (or unfeasible) prices: the upward prices cannot be lower than 60 €/MWh (to be equal or greater than DAM prices in 2017–2019), while downward prices cannot be lower than 0 €/MWh (no negative prices are assumed).

2.5. The multiservice control strategy for simultaneous provision of ancillary services and self-consumption

As mentioned before, the BESS is included in an energy district and aims to provide both self-consumption enhancement and ancillary services to the grid. The adopted strategy aims to first guarantee maximisation of self-consumption, then to bid the BESS' available power and energy margins on ASM. While the rationale and the details of this control strategy were first presented and are better illustrated in [41], we describe in the following how it is implemented in this study.

2.5.1. Available energy margins estimation

To define the available margins in a limited energy reservoir, we consider the energy content at the market gate closure time (GCT) and the estimated energy variation in the next relevant period. Fig. 6 highlights what is meant by the relevant period for available energy estimation, which depends on the market timing. From Fig. 6, we see there is a superposition between market sessions, thus the available energy for the next BM session is related to what has been awarded in the previous session, too. This general framework is used as the basis for the serial analysis. As previously indicated, the analyses will feature different distances to delivery and delivery times.

Estimating energy content at the end of the session reveals the esti-

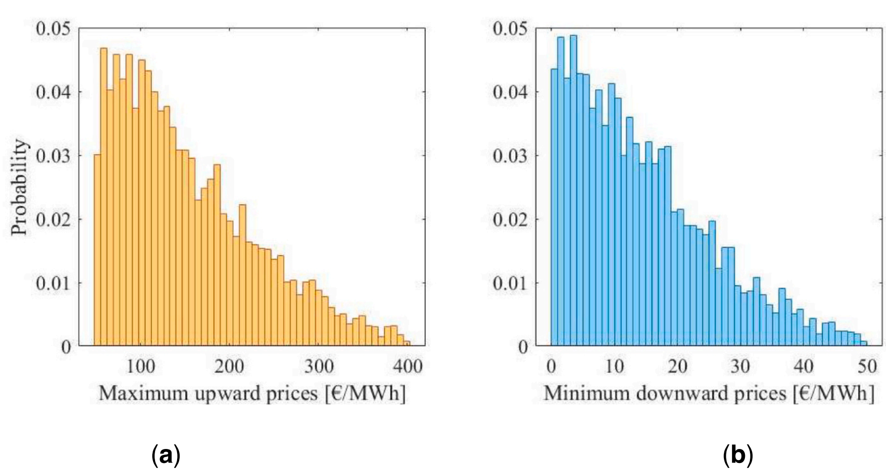


Fig. 5. Outcomes of Balancing Market model relevant to the award/rejection rule: (a) probability distribution of maximum upward prices; (b) probability distribution of minimum downward prices.

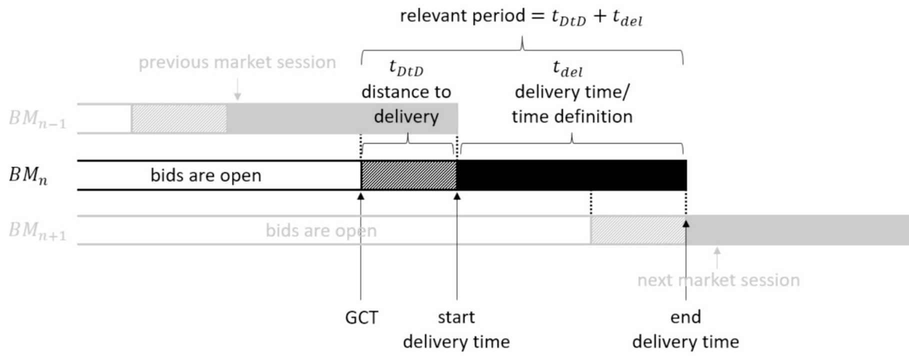


Fig. 6. Schematic view of the balancing market session structure, highlighting the definition of distance to delivery, delivery time and relevant period adopted in this work.

mated available margins with respect to minimum and maximum SoC: these can be offered in the BM. The following elements are of interest when considering the BESS under study (energy flows are positive in case of battery discharging).

- The gap between SoC at GCT ($SoC(h - t_{DtD})$) and SoC_{min} is the margin for upward regulation (ΔE_{up}) at the market closure. Similarly, the gap between SoC_{max} and $SoC(h - t_{DtD})$ represents the energy content for downward (ΔE_{dn}).

$$\Delta E_{up} = \frac{SoC(h - t_{DtD}) - SoC_{min}}{100} * E_n \tag{2.2}$$

$$\Delta E_{dn} = \frac{SoC_{max} - SoC(h - t_{DtD})}{100} * E_n \tag{2.3}$$

- The estimated energy requirement for self-consumption (E_{SCest}) in the next relevant period (as highlighted in Fig. 6) is computed considering the energy district overall control logic illustrated in Paragraph 2.5.3, adopting two separate prediction models for the PV production and the load as detailed in paragraph 3.1. E_{SCest} can be either positive (consumption > production) or negative and is estimated as in (2.4).

$$\begin{cases} E_{SCest} = \sum_{i=1}^{t_{DtD}+t_{del}} \frac{P_{sc\_i}}{\eta_{avgDis}} \; if \; \sum_{i=1}^{t_{DtD}+t_{del}} P_{sc\_i} \geq 0 \\ E_{SCest} = \sum_{i=1}^{t_{DtD}+t_{del}} P_{sc\_i} * \eta_{avgCh} \; if \; \sum_{i=1}^{t_{DtD}+t_{del}} P_{sc\_i} < 0 \end{cases} \tag{2.4}$$

where η_{avgDis} and η_{avgCh} are constant values considering average discharging and charging BESS efficiencies.

- The estimated energy exchange for the provision of previously contracted market services (E_{ASMest}) must be computed. Indeed, the last part of the previous market session occurs after the GCT of the next session. The energy variation impacts the available margin for the next bid. E_{ASMest} is computed as in (2.5).

$$E_{ASMest} = \frac{P_{ASMup}(h - t_{DtD}) * r_{\frac{E}{P}} * t_{DtD}}{\eta_{avgDis}} - P_{ASMdn}(h - t_{DtD}) * r_{\frac{E}{P}} * t_{DtD} * \eta_{avgCh} \tag{2.5}$$

where $P_{ASMup}(h - t_{DtD})$ and $P_{ASMdn}(h - t_{DtD})$ are the awarded power respectively for upward and downward service for the period between GCT and the start of the delivery time. $r_{\frac{E}{P}}$ indicates the hourly MWh requested per each awarded MW. While $r_{\frac{E}{P}}$ is 1 for RR, it is 0.34 for aFRR. This comes from a statistical analysis of the gross energy requested for the provision of aFRR (both upward and downward) in each period of 4 h of 2019 with respect to the awarded power: this means that for 1 MW awarded, the hourly energy provided is 0.34 MWh, with balanced upward and downward requests. It is worth noting that: in case of RR provision, either the first or the latter term (or both) is zero for each hour, since the award of bids is mutually exclusive (either no one or just one bid is awarded); in case of aFRR, awarded upward and downward power can be both nonzero (in particular, they must be equal for symmetric provision).

- The auxiliary system demand (E_{auxEst}) is the estimated auxiliary systems' energy demand for the hours between $[h - t_{DtD}, h + t_{del}]$, obtained by the BESS model [36].

Finally, the available upward and downward energy content are calculated as in (2.6) and (2.7), respectively.

$$E_{avUp} = max(0, \Delta E_{up} - E_{SCest} - E_{ASMest} - E_{auxEst}) \tag{2.6}$$

$$E_{avDn} = max(0, \Delta E_{dn} + E_{SCest} + E_{ASMest} + E_{auxEst}) \tag{2.7}$$

These equations ensure all factors affecting the available energy are considered. Null values are offered on the market in case the energy assessment for one of the two bids yields negative results, i.e., no margins are available. A schematic representation of the available energy estimation for a generic BESS + PV hybrid plant implemented in an energy district is given in Fig. 7. As can be seen, the magnitude of the available energy contents is likely to change due to time of day and previous outcomes on ASM. Indeed, the availability of upward energy (and consequently the maximum feasible upward bid) is usually larger during daytime and in case of previous downward calls (top right of Fig. 7). Oppositely, available energy for downward provision is larger during nighttime and following a previous upward call (bottom left).

E_{avUp} and E_{avDn} are divided by t_{del} hours and by $r_{\frac{E}{P}}$ to obtain the bid quantity in kW. This is checked against the maximum power that can be dedicated to ancillary services provision (P_{maxASM}) as in (2.8) and (2.9). For the sake of the reliability of the provision, P_{maxASM} is 50% of P_n: this is a parameter obtained after a preliminary fine-tuning (this is a simplified hourly check that does not assure the reliability of provision in case of spikes, e.g., due to self-consumption). To avoid micro-bids, a minimum threshold (P_{minASM}) is foreseen, too. This is also to avoid compromising the BESS efficiency, which gets very low for small power output [36].

$$\begin{cases} P_{bidUp} = min\left(\frac{E_{avUp}}{t_{del} * r_{\frac{E}{P}}}, P_{maxASM}\right) \; if \; \frac{E_{avUp}}{t_{del} * r_{\frac{E}{P}}} > P_{minASM} \\ P_{bidUp} = 0 \; elsewhere \end{cases} \tag{2.8}$$

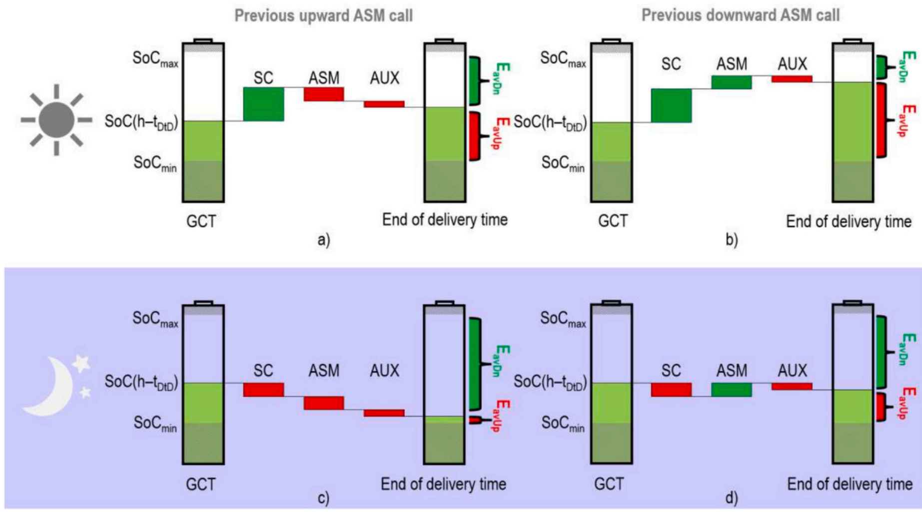


Fig. 7. Schematic representation of the available energy. At the gate closure time, the energy variation for self-consumption (SC), ASM participation and auxiliary demand within the end of the next market session is estimated and available energy is computed. Four cases are shown: a) daytime and upward call in the previous market session; b) daytime and downward call; c) nighttime and upward call; d) nighttime and downward call.

$$\begin{cases} P_{bidDn} = min\left(\frac{E_{avDn}}{4}, P_{maxASM}\right) \ if \ \frac{E_{avDn}}{4} > P_{minASM} \\ P_{bidDn} = 0 \ elsewhere \end{cases} \quad (2.9)$$

Where both P_{bidUp} and P_{bidDn} are absolute values representing the bids for upward and downward reserve, respectively.

If the provision is symmetric, the upward and downward bid quantities must be equal: in a conservative strategy, they are reduced to the minimum between the available quantities.

$$P_{bid}(t) = min(P_{bidDn}(t), P_{bidUp}(t)) \quad (2.10)$$

2.5.2. Balancing market award/rejection rule

After bidding, the BM model returns the award/rejection of the bid. This is based on a purely economic criterion that is aimed to represent a possible simplified TSO's behavior for selecting resources.

- For upward reserve, the bid is awarded if the bid price (to receive) is lower or equal with respect to the maximum awarded price for that market hour.
- For downward reserve, the bid is awarded if the bid price (to pay) is higher or equal with respect to the minimum awarded price for that market hour.

Fig. 8 exemplifies the award/rejection rule for upward service provision. Bids are awarded (accepted, green dot) or rejected (not accepted, red dot) if the bid price ($€_{up}$) is respectively lower or higher than the maximum accepted price for that hour ($€_{upMax}$), considering marginal prices coming from BM model (paragraph 2.4).

As mentioned in paragraph 2.2 either or none of the bids can be awarded for aFRR. In case of RR, no double simultaneous award of downward and upward bids are possible. In case both prices are more convenient than the maximum/minimum, a criterion based on the spread is applied. If the spread between the upward offer and the DAM price is lower than the one between DAM price and downward offer, then only upward offer is awarded, and vice versa. The hourly awarded power on ASM ($P_{ASM}(t)$) is then provided.

2.5.3. The self-consumption logic in an energy district

The considered plant layout is a grid-connected smart energy district [49–51]. It considers an electric load that must be satisfied using local energy production or withdrawal from the grid. The generating assets are a combined heat and power (CHP) plant and a PV plant. A BESS is

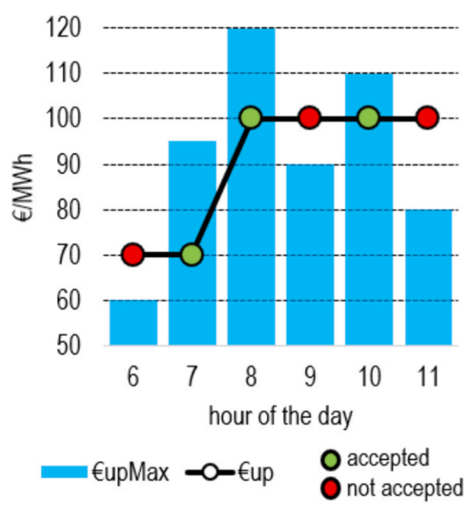


Fig. 8. Award/rejection rule for upward service provision:

also present. The considered energy flows only focus on electricity, while heating needs are disregarded. The layout and the control strategy illustrated below aim to provide a general case study, whose outcomes could be immediately applicable to a large share of DERs and easily extended.

The Reference Case logic considers maximisation of energy self-consumed. Priority is given to PV production, that is consumed as it is available (see eq. (2.11)). The CHP follows the residual electric load ($P_{residual}(t)$) as in eq. (2.12) (i.e., the heat is a by-product, and it is disregarded for the sake of the study).

$$P_{residual}(t) = P_{load}(t) - P_{pv}(t) \quad (2.11)$$

$$P_{CHP}(t) = min(P_{nCHP}, max(P_{tmCHP}, P_{residual}(t))) \quad (2.12)$$

where: $P_{CHP}(t)$ is the CHP setpoint also considering its nominal power (P_{nCHP}) and its technical minimum (P_{tmCHP}), i.e., the power below which the CHP cannot operate safely and should shut off; $P_{load}(t)$ is the load demand; $P_{pv}(t)$ is the PV generation. Therefore, the CHP is never shutting off. The BESS activates if the difference between the CHP setpoint and the residual load is not null.

$$P_{SC}(t) = P_{residual}(t) - P_{CHP}(t) \tag{2.13}$$

where $P_{SC}(t)$ is the requested BESS power for self-consumption. Since the CHP is not shutting off, the $P_{SC}(t)$ can be:

- positive (discharge) in case the residual load is larger than the CHP nominal power;
- negative (charge) in case the residual load is smaller than the CHP technical minimum;
- null elsewhere.

PV and CHP detailed modelling is disregarded, and only the output power profiles are considered. For a better understanding of the self-consumption strategy, please refer to Fig. 10 and paragraph 3.

This priority-based control strategy is optimal in case the PV generation cost is lower than the CHP marginal cost, that is lower than the BESS levelized cost of cycling, that is lower than the spread between bill cost and injection value. The plant layout and the energy flows are proposed in Fig. 9. For the Reference Case just depicted, only the black dashed lines are of interest (no flexibility provision).

2.5.4. Power setpoint for multiservice provision

The overall power requested to the BESS ($P_{req}(t)$) is computed as follows.

$$P_{req}(t) = P_{SC}(t) + P_{ASM}(t) + P_{aux}(t) \tag{2.14}$$

This equation includes the self-consumption enhancement in the energy district ($P_{SC}(t)$) computed as described in paragraph 2.5.3, the provision of ancillary services ($P_{ASM}(t)$) as per the BM award/rejection rule in paragraph 2.5.2, and the feeding of auxiliary systems electric demand ($P_{aux}(t)$) estimated via the auxiliary system model described in paragraph 0. $P_{req}(t)$ is fed to the model as a 1-min setpoint. The $P_{req}(t)$ is checked against the BESS model. The actual power that can be delivered $P_{del}(t)$ could be equal or different from $P_{req}(t)$. Differences can occur if SoC limits are hit, or capability curve limits the power. In case delivered power is different from requested, imbalances occur. If ancillary services request a power provision from/to the grid, this is not accounted as an exchanged power generating imbalance. The power exchanged with the grid ($P_{exch}(t)$) is therefore the difference between request and delivery, net of the ancillary services provision.

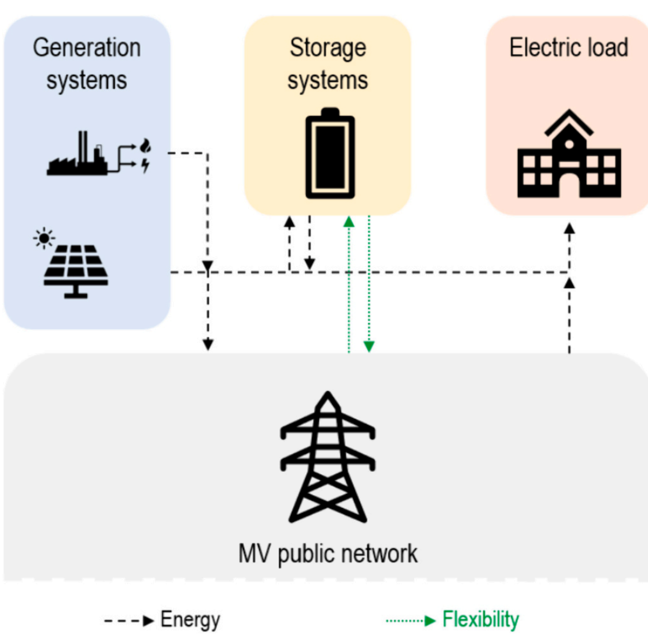


Fig. 9. Plant layout with energy (black) and flexibility flows (green).

$$P_{exch}(t) = \left(P_{req}(t) - P_{ASM}(t)\right) - P_{del}(t) \tag{2.15}$$

It is positive in case of withdrawal, and negative in case of injection.

The adopted Multiservice strategy is not optimized, but it is considered as a possible standard routine for BESS aimed to revenue stacking in the context of an energy district (or, in general, of DERs).

2.6. Assessing the optimal ASM arrangements for opening to DERs

As already pointed out in section 1, the scope of work is to define a possible correlation between each market parameter and the BESS performance. If correlations are found, an optimal range of parameters should be highlighted. The performance should be evaluated from different perspectives. The adopted Key Performance Indicators (KPIs) are listed in the following. The performance of each ASM scheme is checked against a reference case (REF) featuring the provision of self-consumption only, as described in paragraph 2.5.3, without participation to ASM. The energy that can be provided for both the services delivered by the Multiservice strategy is considered. To compare the situation with and without the participation to ASM, the self-consumed energy (E_{sc}) in MWh in each case is evaluated with respect to the E_{sc} in the REF case. This way, we assess if the ASM participation improves the results with respect to a standard BESS control strategy, only devoted to self-consumption. This is considered coherent with the analysis, that aims to return the optimal ASM design for maximising the sum of system's and operators' benefits with respect to no participation. It is worth noting that self-consumption creates not only value for the energy district in terms of avoided costs, but also for the network in terms of reduction of exchanged energy and flows in local distribution network [52–54].

To assess the performance of self-consumption, the total energy requested for self-consumption in MWh is estimated (E_{SCreq}).

$$E_{SCreq} = \frac{t_s}{3600}\sum |P_{SC}(t)| \tag{2.16}$$

Therefore, the E_{screq} is the absolute integral of the power requested for self-consumption and t_s is the sampling time in seconds (in this case, 60 s since the simulation sampling rate is 1 min). The power non-provided for self-consumption ($P_{SC,NP}(t)$) and as a consequence the total non-provided energy ($E_{SC,NP}$) are considered as follows.

$$P_{SC,NP}(t) = min\left(P_{SC}(t), P_{exch}(t)\right) \tag{2.17}$$

$$E_{SC,NP} = \sum |P_{SC,NP}(t)| \tag{2.18}$$

And the actual energy delivered for self-consumption is therefore:

$$E_{SC} = E_{SCreq} - E_{SC,NP} \tag{2.19}$$

In addition, a self-consumption provision ratio (SC%) is estimated as follows.

$$SC\% = \frac{E_{SC}}{E_{SCreq}} \tag{2.20}$$

For what concerns the performance on ASM, both the total energy provided (E_{ASM}) and its reliability are of interest. Reliability is complementary to the nonprovision (NP). Nonprovided power in each instant ($P_{NP}(t)$) is estimated as follows.

$$\begin{cases} P_{NP}(t) = P_{req}(t) - P_{del}(t) - P_{SC,NP}(t)\, if \dfrac{|P_{del}(t) + P_{SC,NP}(t)|}{P_{req}(t)} > 5\% and P_{ASM}(t) \neq 0 \\ P_{NP}(t) = 0\, elsewhere \end{cases} \tag{2.21}$$

where a 5% of inaccuracy in the provision is tolerated and does not entail penalties [55]. NP (in %) is then obtained as the integral of $P_{NP}(t)$ over the E_{ASM}, as follows.

$$NP = \frac{\sum |P_{NP}(t)|}{\sum |P_{ASM}(t)|} \quad (2.22)$$

Both BESS and system operator aim to enhance the flexibility made available by the resource. The energy sold on ASM (E_{ASM}) is estimated as a KPI as the gross total of awarded energy for downward and upward provision. We consider energy since the remuneration on the Italian market is energy-based (€/MWh). Nevertheless, given the importance it has for the system operator, the power available for providing flexibility should be considered, too. To do so, the average power that is bid on the ASM in both upward and downward direction ($P_{bidASMup}$, $P_{bidASMdn}$) is estimated. It is worth noting that the Multiservice strategy considers the ASM participation as a secondary application. The bid quantity, as deeply illustrated in paragraph 2.5.1, is the total available power band, considering the battery limitations and the energy flows devoted to the provision of the main application, that has the priority. Therefore, the P_{bidASM} can be considered the flexibility that can be made available by the DERs, constrained by the market arrangements, and causing no further effort to the energy district. Hence, it is a measure of the available flexibility, given an ASM arrangement. Being able to increase the offered MW on ASM with a fixed installed capacity of resources is something to be pursued by an effective market design [56].

The reliability of provision is a KPI for the system. The provided flexibility should be delivered by keeping as small as possible the difference between the requested energy and the activated energy. The reliability of provision (*Rel*) is estimated as complementary to 1 of the NP, as follows.

$$Rel = 1 - NP \quad (2.23)$$

A higher reliability could foster the penetration of the DERs in ASM, since these resources would be considered trustable as an alternative to reliable conventional generators, traditionally involved in electricity balancing.

The BESS efficiency is a KPI for the operator since BESS variable opex increases if efficiency decreases. In this study, the BESS efficiency ($\eta_{BESSavg}$) is estimated as the average roundtrip efficiency during 1-month operation.

The ASM participation has the goal of improving the economics of BESS operation. To have a general estimation of the BESS net revenues (i.e., providing conclusions that are not bound to a specific regulatory and market framework), the following statements can be proposed.

- The economic attractiveness of the project increases if the self-consumed energy increases. Indeed, self-consumption is generally correlated with avoided costs, but this depends on the entity of grid costs in electricity tariff, that can change [57]. Thus, the high E_{SC} is considered in this study as a minor driver for the economic attractiveness of investments in BESS.
- The flexibility sold on the market is directly correlated with the economic attractiveness of the investment in BESS. As shown in [41], indeed, ASM participation is one of the most remunerative applications for BESS. The E_{ASM} is therefore considered a main driver for improving the economics.
- Non-performance (NP) is generally associated with penalties (NPP) that shrink the net revenues on the ASM. Below a certain threshold, the lack of reliability can even lead to exclusion from the provision (or from the remuneration). Therefore, high reliability is considered a main driver for economics.
- BESS inefficiencies are responsible for additional requested charging energy, thus more opex, but BESS is generally highly efficient. Therefore, BESS efficiency is a minor driver of the economic attractiveness of investment in BESS.

A semi-quantitative economic KPI is included in the results of the study as a combination of the drivers listed above. The equation to compute the overall economic evaluation of each ASM arrangement (EE_i) is the following.

$$EE_i = \sum_{j}^{4} D_{ij} * w_j \quad (2.24)$$

where D_{ij} is a score from 0 to 3 and w_j is a weighting factor based on what just illustrated. Therefore, EE_i returns the sum of the scores of the four drivers for each simulated case *i*. Table 1 reports the values, the weights, and the sources used for defining the scores.

The described KPIs, all together, return a comprehensive evaluation of the suitability of an ASM arrangement for the inclusion of DERs.

3. The case study: An energy district in the tertiary sector that sells flexibility on balancing markets

A wide set of 1-month simulations of BESS operation is performed considering the previously illustrated layout. The difference between each simulation is the ASM arrangement, varying as illustrated in Paragraph 2.1. To characterise the case study with real-world data, the Politecnico di Milano's "Leonardo" Campus is considered. It is the headquarter of the university, characterized by 21 main buildings and >20 thousand students and researchers hosted every day, with classrooms, labs, offices, and shops. Data on this Campus are recorded and made available by the "Commissione Energia", a technical group based in Politecnico di Milano [59].

The energy district of Leonardo Campus can be described as follows [49]:

- a total load of 4000 kW,
- a CHP plant of 2750 kW of nominal power, with a technical minimum of 1375 kW.

A PV generator of 1600 kWp is added in the case study, as per the projects in Politecnico di Milano [60]. In the case study, the CHP operates following the electric load. In addition to this layout, a BESS and the power grid must be considered, as seen in Fig. 9. The BESS data are given in Table 2 and it is modelled as already illustrated. The BESS power is selected to be able to satisfy the peak demand. The sizing in energy is coherent with the maximum daily energy output by the PV obtained with PVGIS [61].

The reference operating strategy for the BESS is to cope with the residual self-consumption requested by the plant, as described in Paragraph 0. The power flows in some standard weekdays and holidays are shown in Fig. 10. The PV generates power during the daytime (in yellow). The electric load (in red) is higher during the daytime but is not null during the nighttime (around 2000 kW). To the left part of the figure, two weekdays are depicted (peak load around 3500 kW). To the right part, Saturday and Sunday are shown (similar pattern, but peak slightly above 2000 kW). The PV production is primarily serving the load. For limited periods, it is injected towards the grid, e.g., at the weekends. The CHP is always on, ranging between the technical minimum and the nominal power, to cope with the residual load (i.e., the difference between the red and yellow curve). Since the CHP provides heating, cooling, and other services to the Campus [62], it is never shut off. Therefore, if the residual load is lower than the technical minimum, the district features an excess in production (e.g. in the morning on weekdays and in weekends). The BESS operates to further enhance self-consumption (see green and purple lines): it is requested to charge when production exceeds the load, it is requested to discharge when generation lacks.

3.1. Energy and power profiles and forecasts

The load and PV profiles of the district for the considered month (June 2021) are presented in Fig. 11. They are retrieved from 15-min average data.

Table 1
Scores and weights for each driver.

#	Drivers	0	1	2	3	Weight (w_j)	Source
1	SC%	<70%	70–80%	80–90%	90–100%	1	[58]
2	E_{ASM} (MWh)	<10	10–50	50–200	>200	2	[22]
3	NP	<90%	90–95%	95–98%	98–100%	2	[55]
4	$\eta_{BESSavg}$	<70%	70–80%	80–85%	>85%	1	[38]

Table 2
Energy district's BESS data.

Key	Value	Unit
Technology	Li NMC	
Nominal power	4	MW
Nominal energy	10	MWh

Table 3
Metadata of the PV and load prediction models.

Key	PV model	Load model
Method	Bagged Tree	Least-square Boosted Tree
Features	*Hour of the day, PV production at h – 24 (i.e., the day-ahead).*	*Hour of the day, day type (i.e., weekday, holiday), Load at h – 168 (i.e., the week ahead).*
Root Mean Squared Error (RMSE)	5.2%	3.6%
Mean Absolute Error (MAE)	2.9%	2.8%

As well as actual power profiles, forecast profiles must be fed to the model for the estimation of the available bands. It is performed with a data-driven model based on classification trees. Two different models are trained for PV and load prediction. The main metadata of the models are given in Table 3, they refer to the prediction of the quantities per unit with respect to their nominal power (thus, they are given in %). It is worth noting that the adopted models are standard, for having generalizable results.

The actual and forecasted power profile are given as input to a Simulink tool, where the BESS model is implemented as well as the model of the district as per the equations presented in Paragraph 2.5.3.

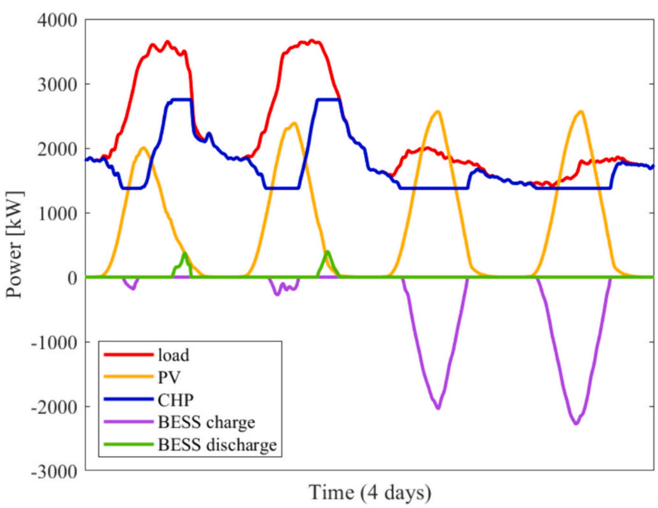


Fig. 10. A sample of the considered power flows in the energy district.

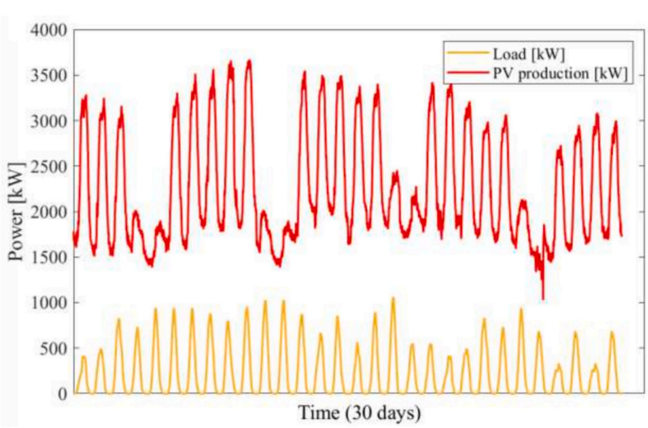


Fig. 11. The load and PV profile for the considered 30 days.

3.2. Setup of the simulations

The simulated case studies differ based on:

- the considered control strategy, that is self-consumption (SC) only in the reference (REF) case (see paragraph 2.5.3), while it is Multiservice in all other cases (see paragraph 0);
- the considered ancillary service and market arrangements, where the previously introduced parameters vary in a range to return a sensitivity analysis of BESS performance under different ASM arrangements.

The study features 25 simulations. The summary of the performed simulations is provided in Table 4. Both aFRR and RR are tested both symmetrically and asymmetrically. The time definition (TD) ranges from 24 h to 1 h. The Distance to Delivery (DtD) ranges from 24 h to zero

Table 4
Layout of the simulation campaign.

Case	Service	Symmetry? [Y/N]	TD [h]	DtD [h]
REF	–	–	–	–
1	aFRR	Y	4	1
2	aFRR	N	4	1
3	RR	Y	4	1
4	RR	N	4	1
5	aFRR	Y	24	1
6	aFRR	Y	8	1
7	aFRR	Y	2	1
8	aFRR	Y	1	1
9	aFRR	N	24	1
10	aFRR	N	8	1
11	aFRR	N	2	1
12	aFRR	N	1	1
13	RR	N	24	1
14	RR	N	8	1
15	RR	N	2	1
16	RR	N	1	1
17	aFRR	N	4	24
18	aFRR	N	4	4
19	aFRR	N	4	0.5
20	aFRR	N	4	0
21	RR	N	4	24
22	RR	N	4	4
23	RR	N	4	0.5
24	RR	N	4	0

(immediate delivery). The several simulations performed are necessary to provide a modular analysis. Between a simulation and the next one, only one parameter (i.e., service, symmetry, TD, or DtD) changes: this allows to detect the specific effect of each parameter on the KPIs. The considered ranges are coherent with the provision of ancillary services in several analyzed markets: indeed, markets are generally characterized by either asymmetric or symmetric procurement, by daily to hourly products, contracted from the day-ahead to real time.

4. Results and discussion

The summary of the resulting KPI for the 25 simulations is given in Fig. 12.

One first consideration is on symmetric RR. In the case of the RR provision (as per the proposed rules), it is meaningless to test the symmetric service: it would result in a simultaneous provision of two constant setpoints of the same magnitude, a positive and a negative one. This is tested in Case 3, where the obtained results are the same as in Case REF since there is no provision on ASM: the results of this test are not proposed in Fig. 12 to avoid confusion, and no more tests with symmetric RR are proposed.

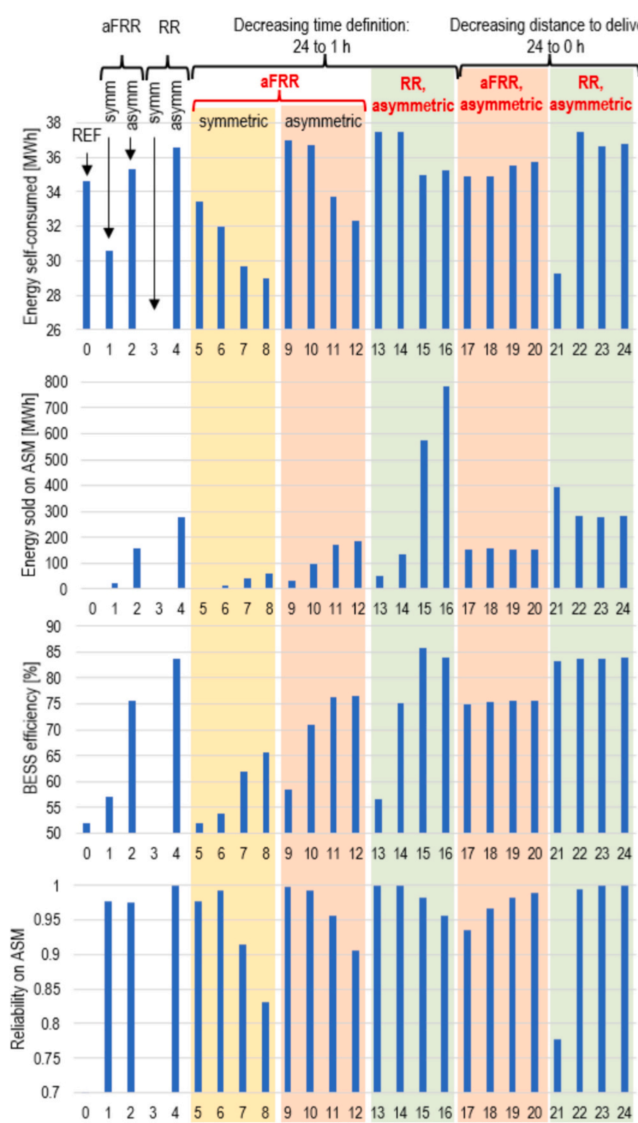


Fig. 12. Main results of the simulation campaign on the ASM arrangements.

4.1. Energy self-consumed

For what concerns the self-consumed energy (E_{SC}), most of the cases show a higher value with respect to REF case. The Multiservice strategy increases self-consumption with respect to the standard control strategy focused on self-consumption only, since the offered margins on ASM work as SoC management. As proposed in Fig. 13 (from case REF = 0, 2, 4), the provision of self-consumption largely requests the BESS to inject power, while the battery charge rarely occurs (e.g., during weekend daytime). Thus, the battery suffers self-discharge due to the auxiliary systems and depletes its energy content. The addition of aFRR and even more of RR allows to increase the battery cycling, avoiding the depletion of SoC and increasing the availability to self-consume.

The increase of self-consumption with respect to REF case always occurs except for Case 1, and 5–8. These Cases feature symmetric provision of aFRR. It does not allow an effective implicit SoC management: the combined effect of the aleatory behavior of aFRR and the reduced bands according to eq. (2.10) do not often support the BESS to restore SoC towards the target. While providing an asymmetric service, the self-consumption is generally high: it is higher for RR than for aFRR. In general, neither TD nor DtD have a strong influence on the self-consumption: self-consumption slightly decreases for small TD, since a larger quantity of energy is offered on the ASM and this leads to competition between the provision of the two services, in the end reducing both the self-consumption and the reliability on the ASM.

4.2. Energy sold on ASM and flexibility

In this paragraph, we analyze both the energy sold on ASM and the flexibility made available on it.

The E_{ASM} is the gross amount of energy awarded on the market, for both upward and downward provision. As presented in Fig. 12, the offered energy largely changes. The simulation 1–4 highlight that a small amount of energy is sold in case of provision of symmetric services: symmetric aFRR only sells 16 MWh of monthly flexibility. The E_{ASM} increases to 148 MWh in case of asymmetric aFRR, and a further step up to 273 MWh sold occurs in case of asymmetric RR.

There is a strong inverse correlation between the energy traded on ASM and the time definition of products. Indeed, a shorter delivery time allows a limited energy reservoir to increase the bid power. An hourly time definition, with respect to a time definition of 4 h, allows to trade from 1.8 (for aFRR, simulation 10 vs 12) to 5.7 times (for RR, simulation 14 vs 16) the E_{ASM}. The energy sold for RR is larger with respect to a coherent provision of aFRR by 1.5 to 4.6 times (comparing simulations 9–12 to 13–16). This is not because the RR is more energy-intensive than aFRR (see eq. (2.5), the aFRR bids are larger to balance the lower energy request) but because of the aleatory behavior of aFRR. Indeed, as can be seen by Fig. 14, comparing SoC distribution of aFRR (left) and RR (right) provision, RR better spans the SoC range. The RR allows to better exploit the energy content of the BESS: e.g., the SoC gets high after delivery of services, thus the P_{bid} is high for upward service, and if awarded, it gets close to minimum SoC, thus allowing offering a large amount of downward reserve for next session and increasing the daily cycles. This is a virtuous circle, since the large energy provision increases the BESS efficiency, thus leading to a SoC distribution considerably shifted towards high SoC.

As said, a requirement for an ASM arrangement to be defined efficient is the possibility to exploit a large amount of flexibility even by a limited installed capacity of resources. The KPI to evaluate this is the average power (P_{bidASM}) that is offered on the market in the simulated month (P_{bidASM}). As per the Multiservice Strategy, this power is represented by the available margin left after providing the primary service (self-consumption, in this case). Focusing on the asymmetric provision, Fig. 15 shows the trend of bid power for aFRR (in red) and RR (in blue). The awarded power depends on the SoC. Nonetheless, the services show differences: at the same SoC, the aFRR can bid a sharply larger power.

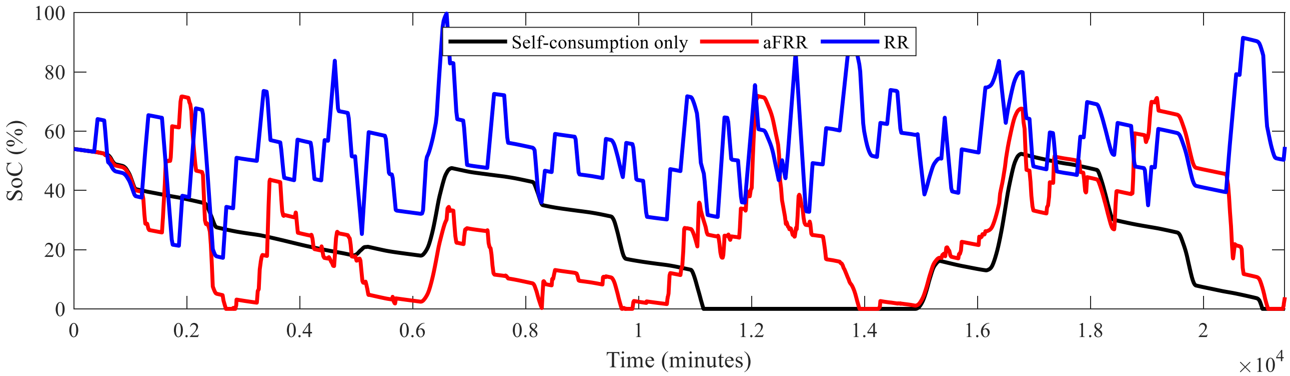


Fig. 13. Fifteen days of SoC evolution during service provision for self-consumption only (REF case in black), for aFRR (Case 2 in red) and RR (Case 4 in blue).

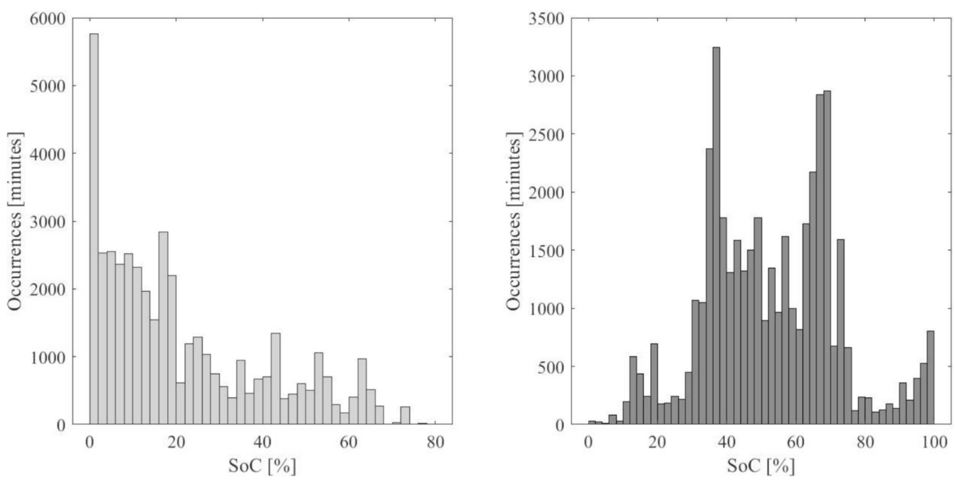


Fig. 14. SoC distribution for aFRR (Case 11, left part) and RR (Case 15, right part).

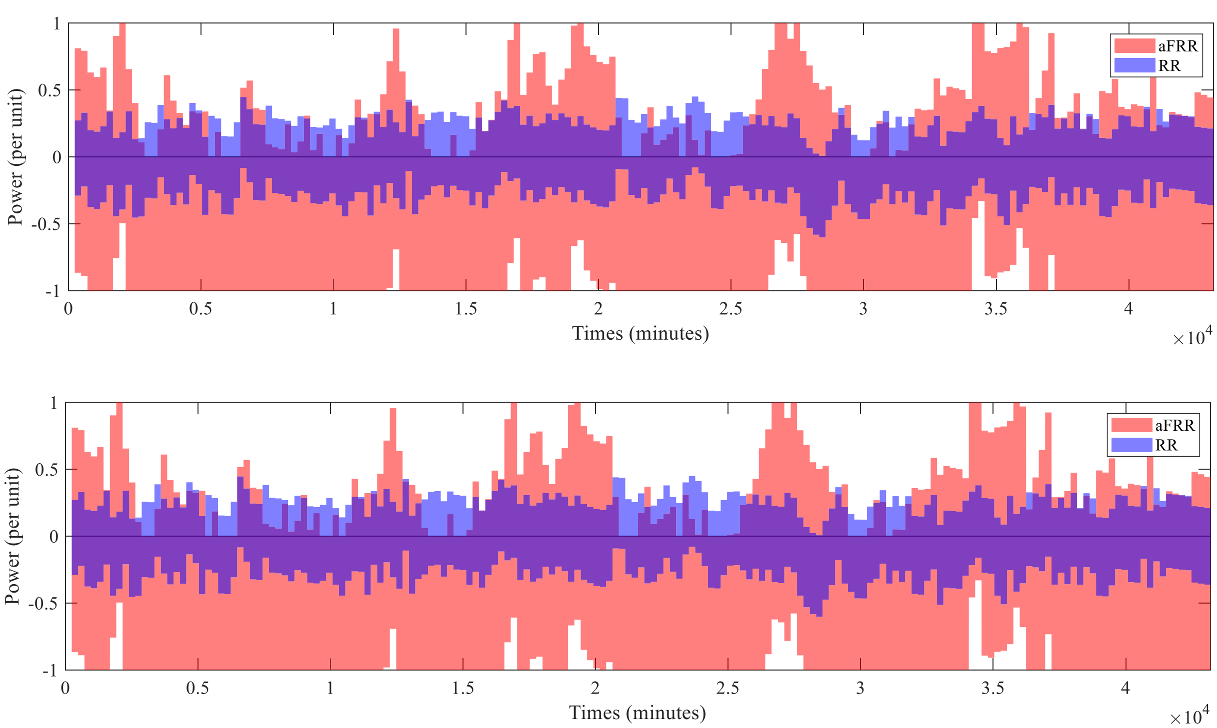


Fig. 15. Bid power (top chart) and SoC (bottom chart) profiles for aFRR (Case 2) and RR (Case 4).

This is because of the smaller energy requirements of aFRR with respect to RR, considered by the Multiservice strategy as per eq. (2.8). In case of a time definition of 4 h, the $P_{bidASMup}$ for aFRR is 1.6 MW, while the $P_{bidASMdn}$ is 3.8 MW (Case 2). For RR, the values are respectively 1.0 and 1.2 MW (Case 4). Reducing the time definition to 1 h, the pair ($P_{bidASMup}$, $P_{bidASMdn}$) for aFRR increases to (2.3, 4.0) MW, and (3.0, 3.5) MW are the values for RR (Case 12 vs 16). Therefore, the bid power is inversely proportional to time definition, too. For aFRR it is generally unbalanced towards downward power. This is because of the lower real-time power flows and the consequently lower efficiencies (and larger weight of auxiliaries) bringing down the SoC. It is worth noting that for low time definitions (e.g., 1 h), in both cases we have 2.4–4.0 MW of flexibility averagely available on the ASM for a BESS of 4 MW of nominal power: this means that 60 to 100% of the installed power can be regularly devoted to flexibility.

4.3. BESS efficiency

The simulations revealed a wide range of average roundtrip BESS efficiencies. Efficiency is very low (down to 45%) for small E_{ASM}. In the REF case, for instance, the minimum efficiency is recorded since the battery is often subject to discharge for feeding the auxiliary systems' demand (see Fig. 13), hence increasing the auxiliaries' share on losses. The efficiency rises to 85% in case of massive participation to ASM. We can conclude that there is interest in exploiting the BESS as much as possible to increase the operating system efficiencies up to doubling them.

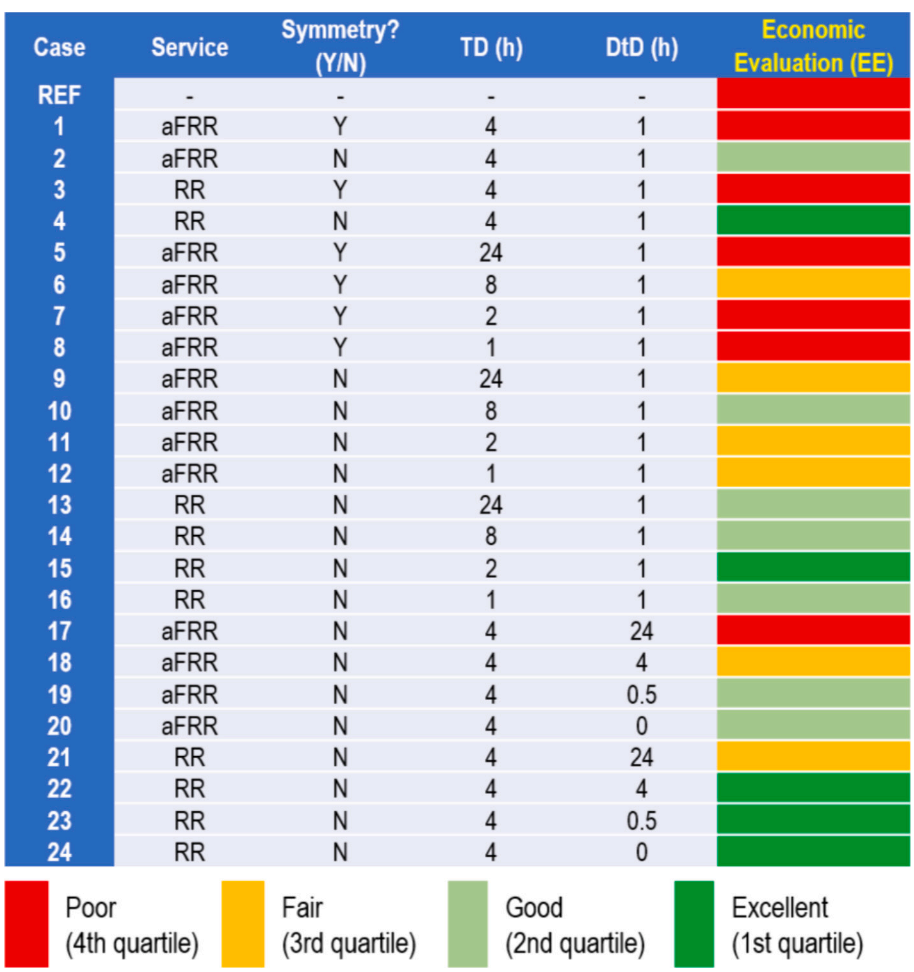
4.4. Reliability of ancillary services provision

The reliability of the provided services is generally high: reliability is above 90% for 20 out of 22 relevant Cases (see bottom chart of Fig. 12). This is given by the effectiveness of the Multiservice Strategy, only bidding what can be provided. In addition, this proves the trustworthiness of BESS and DERs on ASM, thus backing their larger exploitation. The reliability is above 97% for large time definitions (4 to 24 h) and relatively small distances to delivery (<24 h for RR, <4 h for aFRR). This is due to the significantly lower E_{ASM} in these cases. For small time definitions, the traded energy increases, leading sometimes to the impossibility of providing all the energy, e.g., due to SoC saturation. This reduces reliability to smaller, yet acceptable values: around 90% for aFRR and 95% for RR in case of 1 h of time definition.

The effect of the distance to delivery is clearer on the aFRR, since its behavior is aleatory: the provision of aFRR itself can lead SoC to diverge between the commitment (the market closure) and the delivery time, thus leading to unreliability. This is a drawback, for instance, for products contracted on the day-ahead [63].

4.5. Comprehensive economic evaluation and optimal ASM arrangements

To achieve generalizable results, the economic analysis evaluates the set of previously described KPIs that are considered drivers of the economic attractiveness of the investment. The main drivers are the energy traded on the ASM and the reliability in providing the ancillary services. The economic evaluation (EE_i as computed in eq. (2.24)) resulting when considering all KPIs is presented in Fig. 16. In the figure, the colours



Case	Service	Symmetry? (Y/N)	TD (h)	DtD (h)	Economic Evaluation (EE)
REF	-	-	-	-	Poor
1	aFRR	Y	4	1	Poor
2	aFRR	N	4	1	Good
3	RR	Y	4	1	Poor
4	RR	N	4	1	Excellent
5	aFRR	Y	24	1	Poor
6	aFRR	Y	8	1	Fair
7	aFRR	Y	2	1	Poor
8	aFRR	Y	1	1	Poor
9	aFRR	N	24	1	Fair
10	aFRR	N	8	1	Good
11	aFRR	N	2	1	Fair
12	aFRR	N	1	1	Fair
13	RR	N	24	1	Good
14	RR	N	8	1	Good
15	RR	N	2	1	Excellent
16	RR	N	1	1	Good
17	aFRR	N	4	24	Poor
18	aFRR	N	4	4	Fair
19	aFRR	N	4	0.5	Good
20	aFRR	N	4	0	Good
21	RR	N	4	24	Fair
22	RR	N	4	4	Excellent
23	RR	N	4	0.5	Excellent
24	RR	N	4	0	Excellent

Fig. 16. Economic evaluation of each case.

represent the ranking of each simulation: the first quartile is in bright green, presenting the simulations that have an overall economic evaluation included in the first quartile of results, and so on towards red colour, representing the quartile with the lowest economic evaluations.

A poor to fair economic interest is recognized for REF case and for revenue stacking based on symmetric provision of ancillary services. More positive outcomes are shown for asymmetric provision, in particular of RR. AFRR hardly gets an excellent evaluation (1st quartile): a good outcome is achieved for 4–8 h of time definition and for distance to delivery equal or lower than 1 h. The asymmetric RR provision returns excellent economics for 2–8 h of time definition and for distance to delivery lower than 4 h. Apparently, a lower DtD is necessary for services whose energy demand is characterized by an aleatory nature (e.g., depending on frequency deviation or FRCE). In addition, a mid-to-high time window for delivery (TD) is preferable, otherwise the reliability could decrease. Indeed, with a lower TD, a larger power is bid and can lead to strong energy demand in brief time, depleting or saturating the energy content of BESS. The DtD has instead less impact on a service based on static setpoint (as RR).

This analysis helps identifying an optimal range of parameters for standard balancing products. They are shown in Fig. 17. They are coherent with the adopted ranges in the Cases achieving the highest grade of evaluation in Paragraph 4.5.

The results for aFRR can be generalized, up to a certain extent, to all the services showing an aleatory behavior and a low energy intensity. For instance, frequency response services (including Fast Frequency Response) and the services responding to the FRCE. They need to be contracted closer to real time. They can be provided for a generally long period, since they do not require an intense energy provision.

For what concerns the RR (bottom part of Fig. 17), the results can be generalized to the provision of RR, congestion management, balancing and other slow dynamics services. The ranges are larger in this case, and the achieved results are better. Nonetheless, BESS face larger competition when providing services characterized by a static setpoint or by slow dynamics. Indeed, these can be provided by a larger turnout of resources, not only inverter-based systems [64].

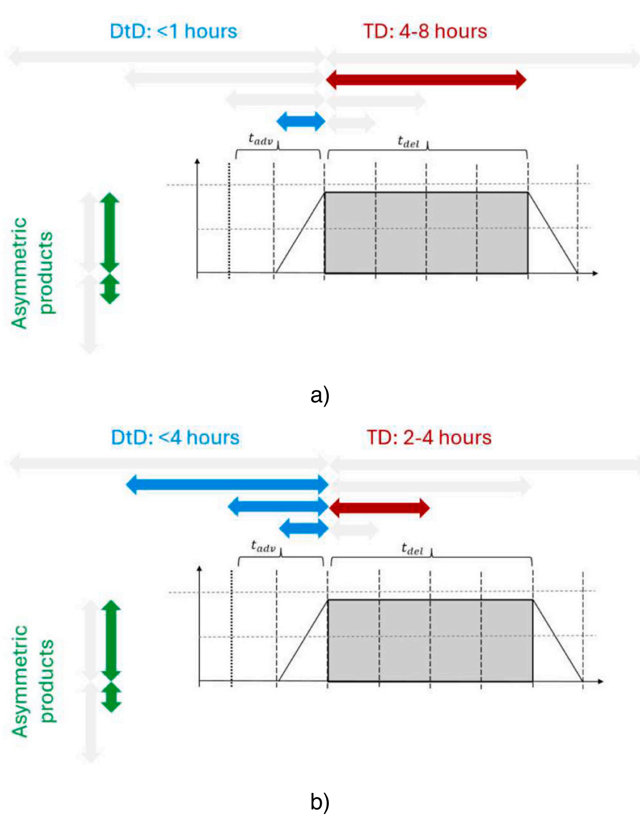


Fig. 17. Optimal ranges for the provision of a) aFRR (top chart) and b) RR (bottom chart).

Concerning distance to delivery, the economic interest towards services traded daily (e.g., a daily auction that occurs the day ahead the delivery) is lower than for products traded just some hours ahead of the delivery. Indeed, if you increase the distance between GCT and delivery time, the compatibility with a revenue stacking vision (that is among the pillars of this study) decreases. As seen in Fig. 12, simulations 17 and 21 show both lower self-consumed energy and reliability on ASM. Logics can be different while deploying BESS integrated in other plants or standalone.

It is worth noting that, within the study, a sensitivity analysis has been performed on the BESS sizing, to check the results with an E/P ranging from 1.5 to 3. This range comes from a previous study, showing that in a revenue stacking framework, with BESS smaller than 10 MW, internal rate of returns larger than 5% are guaranteed for BESS of duration $\leq$3 h [65]. It resulted that the provided outcomes on the optimal BESS arrangement are generally independent from E/P within this limited range.

In conclusion, it should be highlighted that the weights proposed in Table 1 quantitatively influence the results: ASM related KPIs have a large weighting factor since we assume that, today and in the future, BESS will be mostly dedicated to ancillary services provision, where larger revenues can be achieved. Additionally, different pricing mechanisms (e.g., capacity payment in €/MW/period instead of €/MWh), could alter the results quantitatively. Qualitatively, the analysis is considered robust.

4.6. Application to national frameworks

To better address the obtained results and gather some takeaways, the evaluation of real-world examples is provided (see Table 5). Describing the real-world experiences aims to highlight that the proposed evolutions are subject of actual regulatory reviews. It can be useful to understand whether the market reviews head towards a better symbiosis of BESS (and in general DERs) and flexibility markets or not.

Since 2021 the Italian BM changed from a setting with six 4-h market sessions a day, to hourly market sessions. Therefore, the provision of RR in Italian BM was previously represented by Case 4 of this study (see Table 4), while it is now performed as in Case 16. Considering the findings of this work, the expected performance of the energy district change as follows. The offered flexibility and, consequently, the energy traded on the ASM by each BESS is expected to grow sharply. The management of behind-the-meter services could remain the same, as well as the BESS operational efficiency. The reliability of the provision could slightly decrease, maintaining high values (e.g., 95%). Therefore, the evolution is in the direction of further including DERs in the electricity balancing and increasing the flexibility that can be provided by each resource.

Table 5
Model application to national frameworks.

National framework	Service	Previously represented by	Now represented by	Model-based prediction of improvements
Italy	mFRR and RR	Case 4	Case 16	A sharp increase in the volumes of flexibility provided by each BESS.
Italy	aFRR	Case 1	Case 2	Both energy consumption and provided flexibility drastically enhanced.
Germany	FCR	Case 5	Case 1	The study does not highlight major improvements.

For what concerns the provision of aFRR, a pilot project for its asymmetric provision has been presented and activated after 2020 [66]: its final implementation is expected in 2025 (with the issue of the framework document "TIDE" [67]). This change would modify the way aFRR is provided from the one depicted in Case 1 to Case 2. This would drastically improve the techno-economic performance of BESS, increasing the energy traded on ASM by even 7 times – with no expenses on the reliability (see Fig. 12) – and enhancing the self-consumption rates. The economic evaluation would benefit as well, switching a poor evaluation into a good one (see Case 1 vs Cases 2 in Fig. 16).

The study clearly shows a performance decrease in case the gate closure time is too far from the delivery time. Considering the German FCR, the gate closure time is on the day-ahead. The time definition is 4 h since 2019 and the provision is symmetric. Before, time definition was daily. There is not a dedicated Case representing this provision in our study, nonetheless, a symmetric provision of an aleatory service for 24 h is described in Case 5, while 4-h provision is proposed in Case 1 (DtD is always 1 h, which is not the case for Germany). Passing from Case 5 to Case 1 shows no substantial improvement in the overall performance. In real-world, results show that FCR prices did not decrease after the introduction of this new time definition [68]. Furthermore, the decrease in distance to delivery can be of utmost importance in the case of an aleatory service. Cases 17 to 20 support this statement: the reliability increases by 15%, as well as the self-consumption (+21%) and the overall economic evaluation (from "poor" to "good").

The same rationale can be applied to different standard balancing products. The analysis can be extended to evaluate different conditions (e.g., weekly auctions, steeper provision) given the flexibility and low computational effort of the adopted BESS model.

5. Conclusions

In this work, a study on the regulatory barriers for BESS in the provision of ancillary services is presented. The BESS is integrated in a simplified energy district based on the Politecnico di Milano's Leonardo Campus grid. It is selected to be general and to have results that could be applied to a wide range of frameworks. The BESS is providing self-consumption and ancillary services adopting a Multiservice strategy, comprising self-consumption enhancement and ancillary services provision.

The provision of services by BESS shows generally high reliability in a wide span of market arrangements. A larger amount of energy traded on the ASM is not in conflict with the provision of self-consumption: on the contrary, the latter improves as well thanks to synergies exploited by the developed control and bidding strategies. These outcomes strongly support a gradual yet fast penetration of DERs in electricity balancing and in ASM participation. Fine-tuning the parameters allows to retrieve general principles. The asymmetric provision of services (i.e., procuring different downward and upward quantities from a resource) drastically improves the performance, the reliability, and the economic attractiveness of flexibility provision. The different nature of services influence the performance. A static service (i.e., constant power) allows more reliable provision and larger economic benefits. Oppositely, it raises competition since more resources can provide it with high precision. A service requesting to follow an aleatory and dynamic signal slightly reduces reliability and sharply shrinks the traded energy. Yet, it is less energy-intensive, therefore more flexibility (in terms of power) can be offered with the same installed capacity. Eventually, a fast response service decreases the competition electing BESS as the preferential provider. Energy-intensive services benefit of lower time definitions: BESS can offer larger flexibility since it is less constrained by the energy requirements, and the techno-economic performance improves. Aleatory services benefit also of a gate closure closer to delivery time: it is difficult to forecast the available flexibility on a long-term horizon.

The findings and methodology could be applied to optimize a future change in the Grid Codes on balancing services, supporting for instance the decision-making when creating a new service or reforming a standard product, but also to assess a lack of efficiency or a worsening of the techno-economic situation downstream of a reform. To show this latter aspect, the analysis has been applied to recent changes in real-world markets, such as Italian and German frameworks. The model proposes an estimate of the evolution occurred in German FCR that is in line with real-world results. The model estimated no major improvement in the economic evaluation of BESS providing FCR in a 4-h window with respect to daily window; indeed, the real-world prices have not decreased in the period 2020–2021 when the redesign occurred.

The indications and data gathered in this work could be of use for stakeholders (e.g., regulators, policymakers, transmission system operators) aimed to abate the barriers of ASM for an increasingly competitive future market.

CRediT authorship contribution statement

Giuliano Rancilio: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Filippo Bovera:** Writing – review & editing, Methodology, Data curation. **Matteo Spiller:** Software, Methodology. **Marco Merlo:** Writing – review & editing, Project administration, Methodology, Formal analysis, Conceptualization. **Maurizio Delfanti:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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