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Service stacking on residential BESS: RES integration by flexibility provision on ancillary services markets

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ABSTRACT

Opening the Balancing Markets (BMs) to Renewable Energy Sources (RES) and Battery Energy Storage Systems (BESS) could support the integration of RES in decarbonizing power systems; nevertheless, the limited energy content of BESS can reduce their reliability on the BMs. A novel control strategy for revenue stacking of behind-the-meter and front-of-the-meter services on a domestic prosumer equipped with photovoltaic production and BESS is presented in this study. The aim is to maximize self-consumption and the economics while guaranteeing BESS state-of-charge management. A new control (and bidding) strategy is developed to offer the available energy (and power) margins on the Italian BMs, without saturating or depleting the energy content. The results show synergies between self-consumption maximization and flexibility provision, i.e., the proposed approach demonstrates how a multiservice-oriented operation of BESS improves the economic sustainability of the solution, with a payback time between 5 to 9 years, decreases the energy exchange with the public grid and the RES imbalance (imbalance reduced by 90%), and provides flexibility with high reliability (ranging 89%–97%). Due to this, the strategy of reducing the imbalance of variable RES and then providing flexibility with the left margins candidates itself as a standard routine for massively integrating RES via BESS.

1. Introduction

The evolution of power systems and electricity markets sees new distributed energy resources (DERs) connected at Medium Voltage (MV) level increasing their penetration and aiming at entering effectively the several markets, related to energy, capacity, and services [1]. A large share of these units is composed by variable Renewable Energy Sources (RES), such as wind and solar. Their variability and unpredictability could increase the need for power reserves capable to maintain the electricity balancing, namely the equilibrium between generation and consumption in each instant [1]. Power reserves and frequency control are traded on the Ancillary Services Markets (ASMs) in EU [2]. Small, distributed resources (e.g., below 1 MW) are traditionally not enabled in these markets [3]. In any case, the substantial increase in penetration of these resources [4] makes clear the need for involving DERs in electricity balancing [2]. This can be achieved, for instance, via the aggregation of resources in Virtual Power Plants (VPPs) [3].

Battery Energy Storage Systems (BESS) can enable variable RES to ASMs, by reducing their imbalances toward grids and by enabling the provision of ancillary services in RES + BESS hybrid plants [5]. In any case, the massive application of batteries entails issues with the use of scarce materials. This is apparent in the case of Lithium-based batteries, even if progress has been made recently in terms of reusing and recycling materials [6]. On the other hand, sodium-based batteries are under study for a future generation of more sustainable batteries [7].

It is known that BESS can provide accurate and prompt responses to requested power setpoints, but they have a durability issue given by the limited energy capacity [8]. To avoid depletion of the energy content, the control logic of the BESS' operation must implement suitable state-of-charge (SoC) management strategies [9]. SoC management strategies usually encompass a cost, since energy for restoring the SoC towards a target SoC is traded (e.g., purchased) on market. This causes either an additional cost in the electricity bill (in case the energy is withdrawn from the grid) or a missing revenue (in case the battery is in an integrated solution with a RES plant). This type of strategy, namely explicit (or active) SoC management strategies, is analyzed in [10]: it implies costs and enhanced battery aging. Mechanisms for reducing the cost of energy balancing in limited energy reservoirs while providing frequency control are proposed in [11].

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Nomenclature

AC	AlternatingCurrent
ASM	AncillaryServices Market
AUX	Auxiliarysystems
BM	BalancingMarket
BSP	BalancingService Provider
BESS	BatteryEnergy Storage System
BtM	Behind-the-Meter
CAPEX	Capitalexpenditures
XBID	Cross-borderintraday
D	Dayof delivery
DAM	Day-AheadMarket
DC	DirectCurrent
DERs	DistributedEnergy Resources
E/P	Energy-to-powerratio
FtM	Front-of-the-Meter
GHI	GlobalHorizontal Irradiance
KPI	KeyPerformance Indicator
LiB	Lithium-ionbattery
mgmt	Management
mFRR	manualFrequency Restoration Reserve
MV	Mediumvoltage
MW	Megawatt
MWh	Megawatt-hour
NCF	Netcash flow
NMC	Nickel–Manganese–Cobalt
NP	Non-performance
NPP	Non-performancepenalty
BMn	n-sessionof Balancing Market
OPEX	Operationalexpenditures
PV	Photovoltaic
PCS	Powerconversion system
RF	RandomForest
RES	RenewableEnergy Sources
RR	ReplacementReserve
RMSE	Rootmean squared error
SC	Self-consumption
SMA	SimpleMoving Average
SMC	Sodiummetal chloride
SoC	State-of-charge
TIDE	TestoIntegrato del Dispacciamento Elettrico
UVAM	UnitàVirtuali Abilitate Miste
VPP	VirtualPower Plant

On the other hand, BESS' SoC could be managed by providing additional market services (e.g., frequency regulation) with coherent characteristics. Different logics of service stacking can be proposed, usually aiming at revenue stacking; providing multiple services can increase BESS' economics [12,13]. To this aim, dynamic stacking is an effective approach: the BESS provides multiple services simultaneously, devoting to each one a share of power and energy variable in time [14]. A simplified scheme of the dynamic stacking over time can be seen in Fig. 1. Usually, priority is given to the service that shows better economic opportunities. Other services are added in case the main service is not exploiting all the energy/power capability of the BESS or if the additional service has peculiar features improving the general provision [15], for instance improving the BESS reliability.

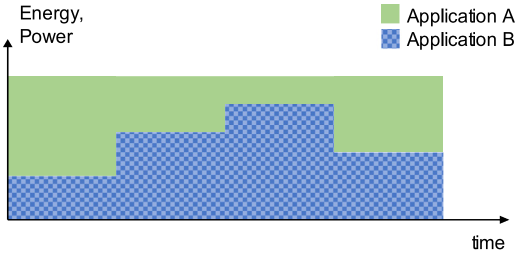

Fig. 1. Graphical representation of the battery capability splitting in case of dynamic stacking. The splitting can be done in terms of energy or power, according to the nature (e.g., energy-intensive, power-intensive) of the services.

It has been shown that asymmetric products are generally more compatible with RES and BESS: they allow to provide different quantities of upward (to inject) and downward (to withdraw) power. Control strategies can be developed exploiting asymmetry for offering the available energy content of the providing asset [16,17]. Nevertheless, in real life conditions, the number of simultaneous services a BESS could manage is limited [18].

In literature, the optimization of BESS control to successfully provide multiple services over a period (e.g., a monthly period [19]) has been already investigated, showing promising results and compatibility with the provision of grid services — even by considering the aleatory nature of loads, distributed generation and frequency. In [20], a BESS providing frequency regulation is evaluated; moreover, a second service (energy arbitrage) has been added managing it as an implicit SoC management and estimating the revenues based on real market prices. In general, the aleatory behavior of the market is disregarded when testing the provision of ancillary services by BESS.

Studies on stationary BESS providing grid services usually adopt a constant [19,20] or a variable efficiency model, generally as a function of the C-rate [21]. More complex models are usually devoted to electric vehicle batteries [22]. As stated in the literature [23], the accuracy of the analysis of BESS operation would benefit of a model considering variable efficiency and the auxiliary losses. A multiparameter empirical BESS model was developed in [24], resulting in high accuracy and reasonable computational effort.

This paper proposes a novel control strategy to provide dynamic stacking with a small-scale domestic BESS, aimed to increase revenues and to improve SoC management in the framework of a national ASM. The BESS is located behind-the-meter of a domestic prosumer equipped with PV. The stacked services are: (i) the improvement of self-consumption and (ii) the provision of manual Frequency Restoration Reserve (mFRR) on ASM. The first service is provided with priority, offering then the available energy and power on ASM. For the latter service, mFRR is selected as the only asymmetric product available as of 2022 on the Italian ASM [25]; the effectiveness of this feature in developing an implicit SoC management strategy is tested. The performances of the control strategy are checked against a reference case with provision of self-consumption only. The results are in terms of technical performance (e.g., energy exchanged with the grid and reliability of the flexibility provision) and economics (e.g., the revenue streams and the net present value of the investment).

The novelties of the study include the development of a methodology for implicit SoC management via ancillary services provision, compatible with a market framework. In addition, the proposed modeling approach is considered more detailed and organic with respect to the literature, as detailed in the following.

- The use of a multiparameter BESS model (considering variable efficiency of battery, power conversion system and

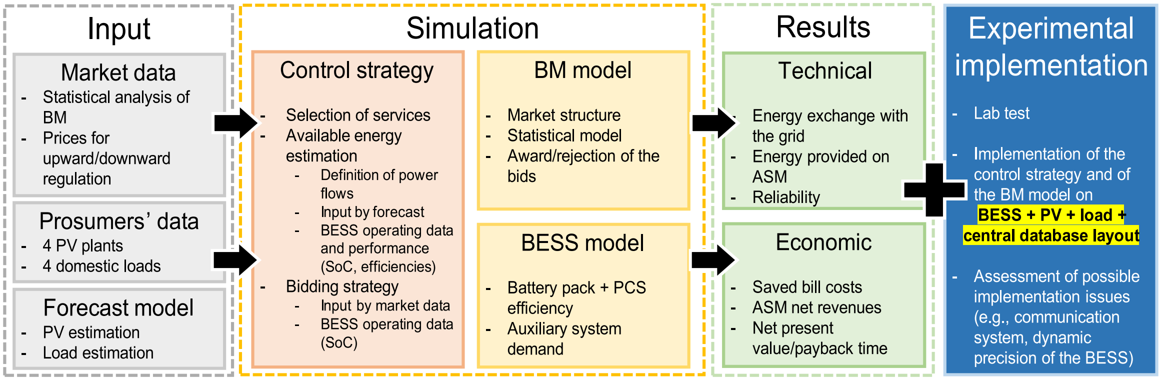

Fig. 2. Graphical representation of the proposed approach.

auxiliary systems) avoids disregarding part of the BESS performance. A high-temperature (high-T) battery technology (Sodium metal chloride) [26] and a standard low-temperature one (Li-ion Nickel Manganese Cobalt) [27] are modeled; it is worthwhile to stress how the auxiliary systems demand could become predominant in the share of losses, especially in the high-T battery. Despite the higher losses, the Sodium-based batteries are selected (among the commercial technologies) since they are studied as a technology that represents a promising sustainable alternative to Lithium-based batteries. Indeed, it does not deal with the use of scarce materials [7].

- The development of a statistical-based Balancing Market (BM) model and of a bidding strategy (tailor-made for finite energy content assets) allows to consider the aleatory nature of the market, particularly the Italian ASM [28]. Generally, while other sources of uncertainty (load, variable RES, weather) are included, market uncertainty is disregarded in studies on flexibility provision. Instead, it plays a relevant role on performance, both on the technical and economic side.

In addition, even if the technical modeling accurately represents the Italian market, a standard balancing product (i.e., manual Frequency Restoration Reserve as per Italian rules) coherent with the EU framework is selected [2].

The adopted data for the considered BESS and prosumers come from the H2020-inteGRIDy project. In particular, they are relevant to the San Severino Marche pilot site, coordinated by Politecnico di Milano, and in cooperation with the local Distribution System Operator ASSEM [29]. As a result, six small-scale batteries were installed and operated, four of them at the PV prosumers' premises and two of them in research labs. Gathered data were used to develop and test the proposed multiple-service control strategy, which combines local self-consumption and provision of mFRR with the objective of maximizing the economic benefits. The experimental tests are not analyzed in the paper, but they successfully implemented the proposed control strategy in real distributed assets. The graphical representation of the work done, better highlighting the modules, tools, and input/output structure, is given in Fig. 2.

The motivation for the study, supported by the outcomes, is showing how a consistent control strategy for RES integrated with BESS, relying on standard inputs and infrastructure (i.e., standard forecast models and procedures, standard communication systems for the eventual creation of a VPP) leads to significant improvements in terms of reliability and economics with respect to standard control strategies (i.e., self-consumption routines). Since this layout (domestic load, BESS and PV) is diffusing in the early 2020s (for instance, in Germany and Italy [30]), enabling it to ASM participation can provide substantial system benefits and represent a cost-efficient RES integration strategy. The developed strategy, exploiting the synergies between services for reducing the RES imbalances with self-consumption, and then offering the left margins as flexibility, candidates itself to be massively deployed to integrate RES in the future power system.

The remainder of the paper is structured as follows. Chapter 2 describes the Italian ASM in the European context. Chapter 3 presents the proposed methodology for both the self-consumption-only case and the multiple-service provision. It illustrates the adopted models and the developed control strategy. Chapter 4 describes the case study, coming from the H2020 inteGRIDy project, and the relevant data collected, and the forecast models adopted. Chapter 5 shows detailed techno-economic results, including the net revenues, the reliability of flexibility provision and the effectiveness of the Multiservice strategy for both the high-T and low-T technologies. Chapter 6 draws the conclusions.

2. The ancillary services market in Italy

To better assess the provision of ancillary services, a detailed market framework is required. The electricity spot markets are generally split into energy markets (day-ahead market and intraday market) and ancillary services markets (ASMs). Generally, participation in the ASM is more suitable to BESS, since they ask a precise power provision for a limited time (generally, 15 min to some hours), both upward and downward (respectively, discharging and charging). The BM includes the ASM session closer to delivery time. Traditionally, the ASM has been opened only to large controllable power plants. However, because of the evolution of the power systems and the new needs in terms of assuring their safe operation, nowadays ASMs are evolving and starting to open also to DERs [3,31,32].

This is the case of Italy, in which the BM is showing an important evolution trend. For example, the UVAM pilot project [33] started in 2018 and admitted DERs to bid on the ASM down to 1 MW of nominal power. Smaller resources could bid on the BM via aggregation, thus creating VPP with consumption, production and storage units belonging to the same market zone. At the time of writing (2022) the UVAM project is allowed to bid for "Other Services" in the Italian BM. It includes the provision of two typologies of frequency regulation,(mFRR) and Replacement Reserve (RR) – and the congestion management. From this point on, we will consider the mFRR provision, otherwise known as tertiary frequency control, on the Italian BM as the investigated flexibility provision. To better detail the service, the following paragraph presents a description of the Italian BM.

The BM in Italy is a pay-as-bid market where 1-hour bids are presented with a price (in €/MWh) and a quantity (in MW). This

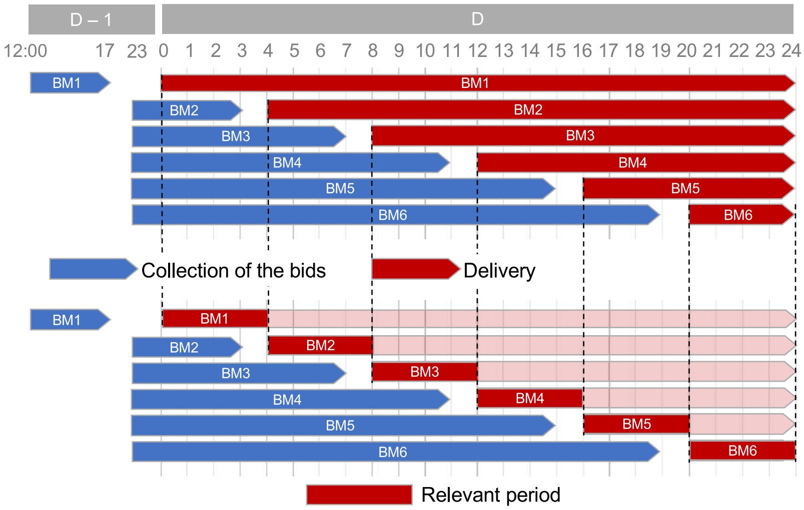

Fig. 3. Structure of the Italian Ancillary Services Market, and the relevant time slot for each session considered by the Multiservice strategy.

market in Italy has traditionally been composed of 6 sessions, as can be seen in the top part of Fig. 3. The first BM session (BM1) opens at noon, the day before the delivery (D-1), just after the closure of Day-Ahead Market (DAM) and closes at 5.30 PM of D-1. The next market session (BM2) opens at 11 PM of D-1 and closes at 3 AM of the day of delivery (D). The following sessions, from BM3 to BM6, open at 11 PM of D-1, as well. Their closures have a shift of 4 h with respect to the previous one. The delivery time of the services that can be contracted in each session starts 1 h after the closure of the market session and ends at midnight of D. In any case, each offer on BM can be updated until the end of the last market session that contracts the hour of interest. Thus, we consider as relevant hours the ones for which the ongoing session represents the last chance to bid. The relevant delivery hours for each BM session are the ones highlighted in dark red in the bottom diagram of Fig. 3. Since DERs improve their forecasts if they bid closer to real time, we can develop an effective bidding strategy by bidding in each session for the relevant hours.

The Multiservice strategy defined within this paper presents bids in each session for the corresponding relevant time slots.

Finally, the European context is fostering the evolution of ASMs. In Italy, this results in the evolution towards an hourly framework for BM sessions to be compatible with the Cross Border Intraday (XBID) Market closures. This transient regulatory framework will probably reach a final steady state with the deliberation of the Integrated Code for the Electricity Dispatch (TIDE in Italian), foreseen for the period 2023–2024 [34].

3. Proposed methodology

As previously introduced, the goal of the study is to develop and test a control strategy able to improve the techno-economic performance of a BESS installed at the residential prosumer premises. To do so, a standard self-consumption routine is compared to a Multiservice strategy, providing both behind-the-meter (BtM) and front-of-the-meter (FtM) services (i.e., ancillary services for frequency regulation). The control strategy takes care of SoC management for the BESS by providing services on the ASM, increasing both the economics and the reliability. A dynamic stacking with two services is foreseen:

- the first service is selected based on economic attractiveness;
- the second one has peculiar features that enable implicit SoC management.

As illustrated in Fig. 1, the control strategy receives input from the field, and from forecast models, it elaborates on considering the market structure and, finally, returns bids compatible with the provision of services with high reliability. The bids are sent to the market model, which returns their acceptance or rejection. The power setpoints (including the provision of the services and auxiliary systems demand) are fed to the BESS model, which returns the provided power, efficiency, and SoC evolution. The outcomes entail the energy provided for each service, the cash flows related to BESS operation, and the reliability of the provision of ancillary services.

This section describes the adopted models for BESS, the statistical model of the ASM developed within this paper and the two control strategies: self-consumption (SC) only and Multiservice, which also includes the bidding strategy for BM. See Table 1 for a list of the adopted symbols.

3.1. Developing an experimental BESS model

Two models are used. The first one is a high-T BESS model representing the Sodium metal chloride (SMC) battery under test in the inteGRIDy project. It is a multiparameter model, obtained thanks to experimental tests and whose preliminary version was presented in [35], that features:

- a different battery efficiency for charging and discharging;
- a constant efficiency for the Power Conversion System (PCS), i.e., the inverter;
- a constant auxiliary power demand, different for charging and discharging;
- a capability chart, showing the maximum available power for both charging at discharging at each SoC.

Instead, a Li-ion NMC battery (LiB) model is taken from the literature [24]. This is because the adopted LiB model has a layout similar to the SMC battery model to be developed. Clearly, the auxiliary system demand is much less relevant, since LiB is a low-T technology.

The adopted models are both BESS oriented, i.e., they do not consider the battery only, but also the PCS and the auxiliary systems. See Table 2 for an essential comparison.

The considered plant layout, also useful for better describing the power flows, is presented in Fig. 4.

In the picture, the following quantities are defined: P_{aux} is the power absorbed by auxiliary equipment, P_{BESSac} is the power exchange with the battery pack, at the a.c. side, P_{pv} is the power

Table 1
Variable and parameters.

Symbol	Definition
P_{aux}	Auxiliary systems demand
P_{BESS_ac}	BESS power delivered on AC side
P_{pv}	PV production
P_{grid}	Power exchange with the grid
$P_{BESS\_ac\_req}$	BESS power required on AC side
η	BESS efficiency
$P_{BESS\_dc\_req}$	BESS power required on DC side
P_{BESS_dc}	BESS power delivered on DC side
P_{max_dis}	Maximum discharge power
P_{max_ch}	Maximum charge power
SoC_{min}	Minimum SoC
SoC_{max}	Maximum SoC
E_n	Nominal energy
S	Sampling rate
$SoC(t)$	State-of-charge at time t
P_{inj}	Power injected to the grid
P_{with}	Power absorbed from the grid
P_{bidUp}	Upward bid power
P_{bidDn}	Downward bid power
P_{ASM}	Awarded power on ASM
$€_{ASM}$	Awarded price on ASM
ΔE_{up}	Energy margin for upward ASM
ΔE_{dn}	Energy margin for downward ASM
E_{SCest}	Estimated energy for self-consumption
E_{ASMest}	Estimated energy for ASM
E_{AUXest}	Estimated energy for auxiliaries
$P_{predLoad}$	Predicted power demand for loads
P_{predPV}	Predicted power demand for PV
$P_{load,d,j}$	Historical data on power demand for load on day d, hour j
P_{bidUp}	Bid power for upward ASM
P_{bidDn}	Bid power for downward ASM
$€_{up}$	Bid price for upward service
$€_{dn}$	Bid price for downward service
$€_{upMer}$	Bid price for upward service in case of merchant strategy
$€_{dnMer}$	Bid price for downward service in case of merchant strategy
$€_{upRel}$	Bid price for upward service in case of reliability strategy
$€_{dnRel}$	Bid price for downward service in case of reliability strategy
$€_{upSpread}$	Spread for the injected (upward) MWh on ASM or DAM
$€_{dnSpread}$	Spread for the withdrawn (downward) MWh on ASM or DAM
X_{up}	Boolean upward: 1 if awarded, 0 if rejected
X_{up}	Boolean downward: 1 if awarded, 0 if rejected
E_{exch}	Absolute value of the exchanged energy excluded ASM energy
E_{upASM}	Awarded energy for upward ASM
E_{dnASM}	Awarded energy for downward ASM
P_{NP}	Non-performance power on ASM
NP	Share of non-performance on total awarded power on ASM
C_{bill}	Bill cost
$€_{DAM}$	Zonal price on DAM
$€_{fee}$	Penalty for non-performance on ASM
R_{SC}	Net revenues from self-consumption
R_{ASM}	Net revenues from ASM participation
k_e	Energy factor for computation of CAPEX (€/kWh)
k_p	Power factor for computation of CAPEX (€/kW)

Table 2
Comparison between the BESS models for the 3 kW, 8 kWh battery adopted in the study.

Technology	SMC	Li-NMC
Battery efficiency	Constant, different for charge (87%) and discharge (98%)	Variable between 54 and 95%, as a function of power and SoC, see [24]
PCS efficiency	Constant (85%)	
Auxiliary systems demand	Constant, different for charge (225 W) and discharge (120 W)	Variable between 7 and 37 W, as a function of ambient temperature and power, see [24]

injected by the PV generator, P_{load} is the power absorbed by the load and, finally, P_{grid} is the power exchange with the main grid.

3.2. Behind-the-meter control strategy

The first control law implemented is devoted to maximizing self-consumed energy. The tool receives as input the SoC, the P_{pv} and P_{load} in each instant. In the general case, the First Kirchhoff Law (see Fig. 4) mandates that the power supplied by the battery is $P_{BESS\_ac}(t)$ is computed as:

$$P_{BESS\_ac}(t) = P_{load}(t) + P_{aux}(t) - P_{pv}(t) - P_{grid}(t) \tag{1}$$

where $P_{grid}(t)$ represents the exchange with the distribution grid and is positive when power is absorbed from the grid. Following the SC logic, the objective function is to minimize the exchange with the grid during the entire observed period T, ideally to zero.

$$minimize\ P_{grid}(t), \quad \forall t \in T \tag{2}$$

According to this objective of minimizing the exchange of the grid, the requested AC power to the battery $P_{BESS\_ac\_req}(t)$ (i.e. the ideal power that the BESS must absorb to nullify the exchanges with the grid) will always be calculated as:

$$P_{BESS\_\text{ac}\_req}(t) = P_{load}(t) + P_{aux}(t) - P_{pv}(t) \tag{3}$$

As it can be seen from (1) and (3), it is important to consider that the BESS always has auxiliary systems that must be fed. Therefore, the battery pack charges in case the PV generation is larger than the energy demand by the domestic loads and the auxiliaries, otherwise it discharges. Then, the efficiency of the battery represents the ratio between the powers on the AC and DC side, considering both the efficiency of the battery itself and the inverter's one. The efficiency of the battery $\eta(t)$ is a function of the parameters presented in 4.1.

$$\eta(t) = \eta\left(SoC(t-1), P_{BESS\_\text{ac}\_req}(t)\right) \tag{4}$$

Once the power requested by the SC logic is known, the power on the DC side that affects the SoC in the empirical model of the battery is then calculated as:

$$\begin{cases} P_{BESS\_dc\_req}(t) = \frac{P_{BESS\_ac\_req}(t)}{\eta(t)}, & if\ P_{BESS\_ac\_req}(t) > 0 \\ P_{BESS\_dc\_req}(t) = P_{BESS\_ac\_req}(t) * \eta(t), & if\ P_{BESS\_ac\_req}(t) \leq 0 \end{cases} \tag{5}$$

Of course, the objective of minimizing the exchange with the grid is subject to its power capability curve (defined in 4.1) and the SoC of the battery itself. The power exchange of the battery, both for charging and discharging, is calculated based on the last known SoC value at t-1:

$$\begin{cases} P_{BESS\_dc}(t) = \min\left(P_{BESS\_dc\_req}(t), P_{\max\_dis}(SoC(t-1))\right) \\ \qquad if\ P_{BESS\_dc\_req}(t) > 0 \\ P_{BESS\_dc}(t) = \min\left(-P_{BESS\_dc\_req}(t), P_{\max\_ch}(SoC(t-1))\right) \\ \qquad if\ P_{BESS\_dc\_req}(t) \leq 0 \end{cases} \tag{6}$$

where $P_{\max\_dis}$ and $P_{\max\_ch}$ represent the maximum power that can be delivered at SoC(t-1), always taking positive values. Consequently, it is assumed that the battery would be able to provide the given set point P_{BESS_dc}. Finally, since P_{BESS_dc} is the power actually flowing in the battery, the SoC is updated as in the following:

$$SoC(t) = \max\left(SoC_{min}, \min\left(SoC_{max}, SoC(t-1) - \frac{P_{BESS\_dc}(t)}{E_n * S * 3600} * 100\right)\right) \tag{7}$$

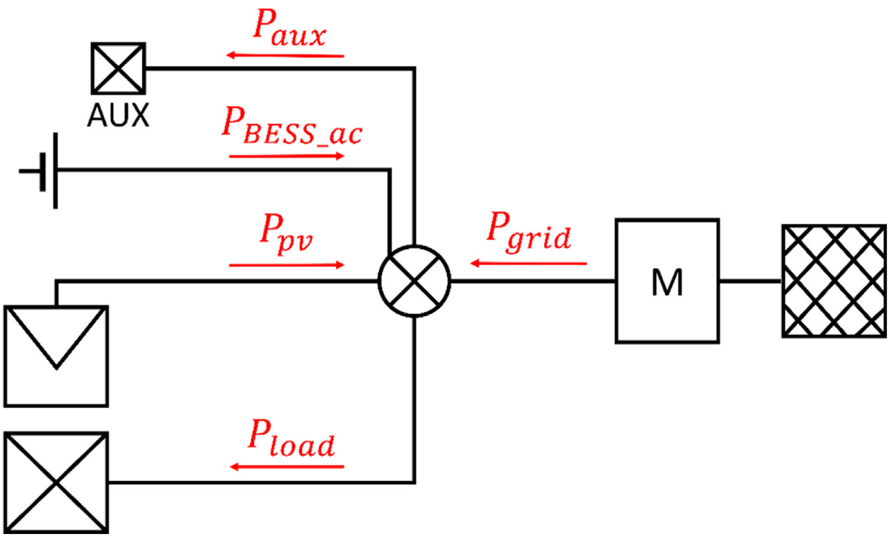

Fig. 4. Plant scheme composed by (from top to bottom, from left to right) the auxiliary systems, the battery, the PV generator, the loads, the meter (M), and the connection with the public grid. The considered power flows are shown in red.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where the equation is generalized with S which defines the sampling rate or the frequency of assigning set points to the battery. The multiplication of S by 3600 s per hour generalizes the transformation from power to energy. Then, exchanged energy is divided by E_{n} and multiplied by 100 to have the SoC variation for each step. Finally, the estimated SoC is compared with the upper ($\mathrm{SoC_{max}}$) and lower boundary of SoC ($\mathrm{SoC_{min}}$), which are the upper and lower boundary of admitted SoC. In case the requested power $P_{BESS\_dc}(t)$ leads to one of the SoC boundaries being reached, it is updated as follows to consider the energy constraint of the battery:

$$\begin{cases} P_{BESS_{dc}}\,(t) = (SoC\,(t-1) - SoC_{max}) * E_n * S * \frac{3600}{100}, \\ \qquad if\ SoC\,(t) = SoC_{max} \\ P_{BESS_{dc}}\,(t) = (SoC\,(t-1) - SoC_{min}) * E_n * S * \frac{3600}{100}, \\ \qquad if\ SoC\,(t) = SoC_{min} \end{cases} \tag{8}$$

Finally, if the power requested in (3) leads to some of the constraints being violated, a different power provided is obtained, i.e. $P_{BESS\_ac}\,(t) \neq P_{BESS\_ac\_req}\,(t)$. In such a case, it needs to be recalculated applying the efficiency to $P_{BESS\_dc}\,(t)$.

$$\begin{cases} P_{BESS\_\mathrm{ac}}\,(t) = P_{BESS\_dc}\,(t) * \eta(t)\ if\ P_{BESS\_dc}(t) > 0 \\ P_{BESS\_\mathrm{ac}}\,(t) = \frac{P_{BESS\_dc}(t)}{\eta(t)}\ if\ P_{BESS\_dc}(t) \leq 0 \end{cases} \tag{9}$$

$P_{BESS\_ac}\,(t)$ represents the power that can be measured on the AC side. Theoretically, in each instant t it should be equal to the power that is requested $P_{BESS\_ac\_req}\,(t)$, leading to $P_{grid}\,(t) = 0$ and optimizing the revenue in the electricity bill. However, this is hardly achievable without vastly over-dimensioning the BESS; otherwise, the prosumer will have to exchange energy with the grid. For each time instant t, we can define two separate vectors for injection $P_{inj}(t)$ and withdrawal $P_{with}(t)$.

$$\begin{cases} P_{inj}\,(t) = min\left(0, P_{BESS_{ac}}\,(t) - \mathrm{P}_{BESS\_req\_AC}\,(\mathrm{t})\right) \\ P_{with}\,(t) = max\left(0, P_{BESS_{ac}}\,(t) - P_{BESS\_req\_AC}\,(t)\right) \end{cases} \tag{10}$$

where $P_{inj}(t)$ is negative in case grid injection occurs, 0 elsewhere; $P_{with}(t)$ is positive in case withdrawal from the grid occurs, 0 elsewhere.

3.3. Multiple services provision: Simultaneous provision of self-consumption and ancillary services

As already introduced, it is of interest to investigate a BESS service stacking control logic. Service stacking can be used to increase revenues, as well as to enhance the reliability of the provision. One common approach is to elect a service as the main service, and the others as secondary ones [19]. The main service has the priority: the most economically rewarding service is selected as main service. The statistical analysis presented in Fig. 5 shows the average economic spread between discharging revenue and charging cost for a BESS providing the three main services available for small customers in Italy, as of 2023: arbitrage, participation to balancing market and self-consumption provision. This is obtained by considering, for year 2019, average spread on DAM (arbitrage) [25], average spreads for BM [36], and the average difference between bill cost and injection value for a domestic customer [37]. Therefore, the selected priority service is self-consumption enhancement.

Hence, the SC logic is guaranteed whenever possible; in particular, in the proposed approach, power and energy contents not required for the self-consumption goal are offered on the BM by the Multiservice strategy. The flowchart of the proposed Multiservice control strategy is given in Fig. 6 and described in the following.

During the nighttime, when the PV production is lower than the load consumption, a downward reserve could be provided. Vice versa during the daytime of sunny days, PV production overcomes the load, the battery charges and therefore upward energy is available. The provision of ancillary services aims to prevent the depletion of SoC at the lower boundary ($\mathrm{SoC_{min}}$) during the night or saturation at the upper boundary during the day ($\mathrm{SoC_{max}}$). Indeed, the market bidding strategy is based on the battery's SoC: if the SoC(t) is higher than a target SoC (arbitrarily set at 50%), the strategy offers on the market more upward service than downward (to discharge the battery), and vice versa. Assuming that for time = t, a bid on the market with a value $P_{ASM}\,(t)$ has been selected, the power requested to the battery is updated as in (11).

$$P_{BESS\_ac\_req}\,(t) = P_{load}\,(t) + P_{aux}\,(t) - P_{pv}\,(t) + P_{ASM}(t) \tag{11}$$

where P_{ASM} is the power exchanged with the grid for the provision of ancillary services, positive for a request to provide upward

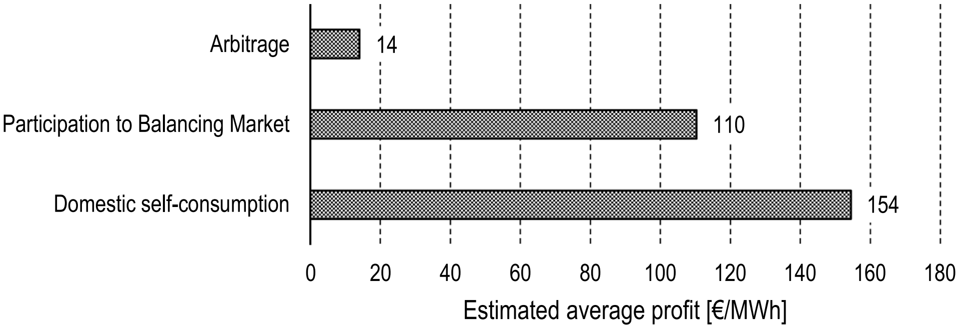

Fig. 5. Average spread between discharge value and charge cost for each service in 2019.

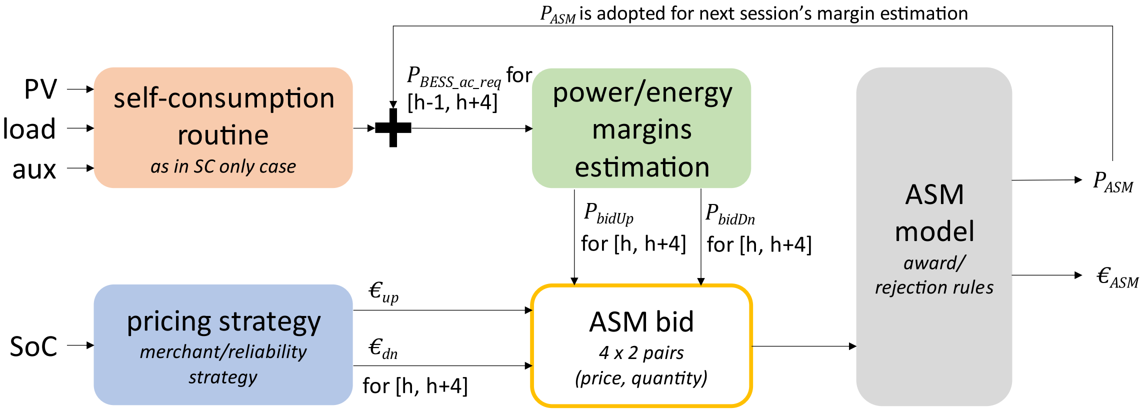

Fig. 6. Flowchart for the Multiservice routine.

reserve and negative for downward. Similarly to the checks performed for the SC strategy demonstrated with Eqs. (4)–(9), a value for the feasible power set point $P_{BESS\_ac\_req}(t)$ is obtained. Consequently, the objective function of the control logic is to minimize the difference between the power set point agreed on the ASM and the actual one:

$$minimize\ P_{grid}(t) - P_{ASM}(t), \quad \forall t \in T \tag{12}$$

This means reducing the exchange with the grid except for the power provided on ASM. Not being able to provide the agreed set point to the ASM leads to non-performance penalties, detailed later in the chapter.

The modeling tool implements a simplified market model of the Italian ASM, a controller for available energy estimation (both upward and downward) and a bidding (pricing) strategy. As detailed before, Italian ASM is divided into ex-ante and BM sessions and trades several products: the residential BESS is only bidding on BM for mFRR. Each day, six couple of bids (i.e., upward and downward bids) are proposed at the BM gate closures, for the relevant period of each BM session (see Fig. 3, bottom part). Thus, for each market session starting at time h, a bid is presented at time $h-1$, with each bid containing the energy quantities (in kWh) and the prices (in €/MWh) for hour h to $h{+}4$.

3.3.1. Available energy estimation and bid quantity

The bid quantity is put equal to the available margins of the battery, considering the energy flows during the next market session. To do so, we define the energy content at the market closure and the estimated energy variation in the next period. Computing the estimated energy content at the end of the session will reveal the available margins to be offered on the BM. Considering the operation of the battery under study, the following elements are of interest.

- The gap between SoC at market closure $SoC\,(h-1)$ and SoC_{min} is the margin for upward regulation (ΔE_{up}) at the market closure. Similarly, the gap between SoC_{max} and $SoC\,(h-1)$ represents the energy content for downward (ΔE_{dn}).

$$\Delta E_{up} = \frac{SoC\,(h-1) - SoC_{min}}{100} * E_n \tag{13}$$

$$\Delta E_{dn} = \frac{SoC_{max} - SoC\,(h-1)}{100} * E_n \tag{14}$$

- The estimated energy requirement for self-consumption (E_{SCest}) in the next 5 h (including the hour between market closure and next session start and the 4 h of each market session) is computed with two separate prediction models for the PV production and the load, detailed in paragraph 4.3.2. E_{SCest} can be either positive (consumption > production) or negative and is estimated as in (15).

$$\begin{cases} E_{SCest} = \sum_{i=0}^{4} \left(P_{predLoad\_i} - P_{predPV\_i}\right) * \frac{1}{\eta_{avgDis}} \\ \qquad if \sum_{i=0}^{4} \left(P_{predLoad\_i} - P_{predPV\_i}\right) \geq 0 \\ E_{SCest} = \sum_{i=0}^{4} \left(P_{predLoad\_i} - P_{predPV\_i}\right) * \eta_{avgCh} \\ \qquad if \sum_{i=0}^{4} \left(P_{predLoad\_i} - P_{predPV\_i}\right) < 0 \end{cases} \tag{15}$$

where P_{predLi} and $P_{predPVi}$ estimate the load and PV production for hour i in kW; η_{avgDis} and η_{avgCh} are constant values for the average discharging and charging BESS efficiencies (assuming 92% as the average efficiency for Li-NMC BESS and adopting the values in Table 2 for the SMC BESS [24]).

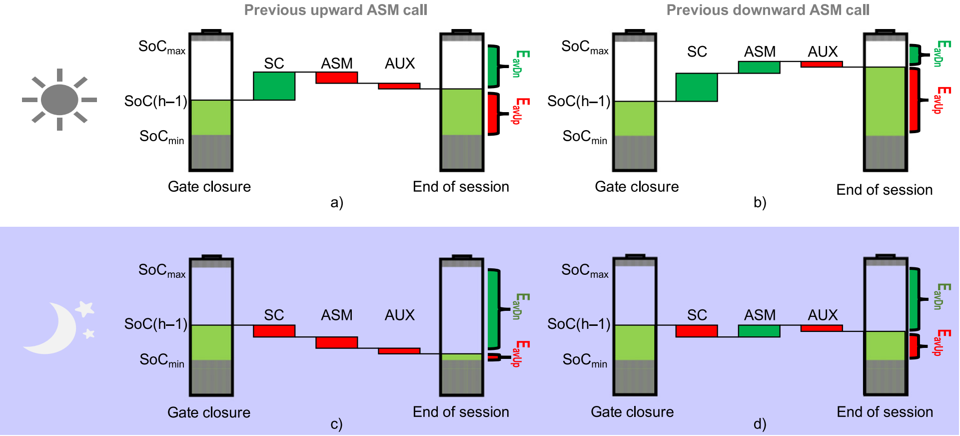

Fig. 7. Schematic representation of the available energy. At the market gate closure (h-1), the energy variation for self-consumption (SC), ASM participation and auxiliary demand within the end of the next market session (5 h) is estimated and available energy is computed. Four cases are shown: (a) daytime and upward call in the previous market session; (b) daytime and downward call; (c) nighttime and upward call; (d) nighttime and downward call.

- The estimated energy exchange for the provision of previously contracted market services (E_{ASMest}) must be computed. Indeed, the last hour in the previous market session corresponds to the $h-1$ to h period. The energy variation impacts the available margin for the next bid. As it was previously mentioned, mFRR contracts a resource either for upward or downward service each hour. Therefore, E_{ASMest} is computed as in (16).

$$E_{ASMest} = \frac{P_{ASMup}(h-1) * 1h}{\eta_{avgDis}} - P_{ASMdn}(h-1) * 1h * \eta_{avgCh} \quad (16)$$

where $P_{ASMup}(h-1)$ and $P_{ASMdn}(h-1)$ are the awarded power respectively for upward and downward mFRR for the period $[h-1,\ h]$. As per what was previously stated, either the first or the latter term (or both) is zero for each hour.

- The auxiliary system demand (E_{auxEst}) is the average auxiliary energy demand for the 5 h between $[h-1,\ h+4]$.

Finally, the available upward and downward energy content are calculated as in (17) and (18), respectively.

$$E_{avUp} = \max\left(0,\ \Delta E_{up} - E_{SCest} - E_{ASMest} - E_{auxEst}\right) \quad (17)$$

$$E_{avDn} = \max\left(0,\ \Delta E_{dn} + E_{SCest} + E_{ASMest} + E_{auxEst}\right) \quad (18)$$

These equations assure all factors affecting the available energy for both services are considered and no negative values are offered on the market in case the energy assessment for one of the two bids yields negative results. A schematic representation of the available energy estimation is given in Fig. 7. As it can be seen, the magnitude of the available energy contents is likely to change due to the moment of the day when the market session occurs and the previous outcomes on the ASM. Indeed, the availability of upward energy (and consequently the maximum feasible upward bid) is usually larger during daytime and when in the previous market session the BESS had been awarded a downward bid (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 4 h 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 (19) and (20). Of course, this is a simplified hourly check that does not assure that there would not be any issues during the real-time operation since it is based on average hourly values. 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. To avoid micro-bids, a minimum threshold (P_{minASM}) is foreseen, too. For the analysis in this paper, P_{minASM} is equal to 200 W.

$$\begin{cases} P_{bidUp} = \min\left(\frac{E_{avUp}}{4}, P_{maxASM}\right) & if\ \frac{E_{avUp}}{4} > P_{minASM} \\ P_{bidUp} = 0 & elsewhere \end{cases} \quad (19)$$

$$\begin{cases} P_{bidDn} = \min\left(\frac{E_{avDn}}{4}, P_{maxASM}\right) & if\ \frac{E_{avDn}}{4} > P_{minASM} \\ P_{bidDn} = 0 & elsewhere \end{cases} \quad (20)$$

where both P_{bidUp} and P_{bidDn} are absolute values representing the bids for upward and downward reserve, respectively. It should be noted that in this case, these bids represent hourly values, so the energy offered is also the power set point during that specific hour.

3.3.2. Load and PV forecasting

As discussed in paragraph 4.3.1, the multiple services provision requires an estimation of the available energy for the provision of mFRR. Following equations (17) and (18), the energy estimation performed for each market session (h) is based on the SoC(h-1), the mFRR set point between [h-1,h] and the forecasted self-consumption profile of the user for the time period [h-1,h+4], since the duration of each session is 4 h and the bidding is 1 h prior to the start of the session. This subchapter is concerned with the self-consumption estimation, by separately forecasting the load and PV production during the 5 h of interest, which are then used in (15) to evaluate the SC profile. It is worth noting that the adopted forecasting procedure is a standard approach: this assumption is taken to focus the work on the control strategy development. Indeed, if the control strategy shows effectiveness with a standard method, then it can be improved with more sophisticated ones.

Both forecasting procedures are performed based on a sliding window, suggesting that the forecast is performed at the time of submitting the bid at h-1 where h is the starting hour of each market session. Both PV and load estimations are performed individually for each user.

Machine learning techniques are widely adopted for the purpose of PV production forecasting [38], with various research suggesting that the Random Forest (RF) algorithm provides high accuracy even when using smaller datasets for the training phase [39,40]. The PV forecast developed for the project is a hyperparameter-optimized RF algorithm for regression that provides hourly estimation for the PV production of each user, detailed in [40]. The PV production forecast is based on an RF algorithm considering weather parameters such as the global horizontal irradiance (GHI), temperature, humidity, and wind speed as features. It uses the historical GHI from the closest point to the user and a time-vector as input features, correlating them to the historical power output of the PV plant. Then, a prediction for $P_{predPVi}$ where $i \in$[h-1, h+4] is performed by correlating the GHI from the weather forecast for those 5 h with the corresponding time vector.

Table 3
Merchant/reliability strategy summary table.

Key	Value
SoC_{hi}	75%
SoC_{lo}	50%
SoC_{max}	95%
SoC_{min}	30%
$€_{upMer}$	100 €/MWh
$€_{upRel}$	70 €/MWh
$€_{dnMer}$	20 €/MWh
$€_{dnRel}$	30 €/MWh

A simplified approach adopting the moving average is used, instead, for the load prediction. In general terms, the estimation for the consumption P_{predLi} where i ∈[h-1, h+4], is computed as in:

$$P_{predLoad\_i} = \frac{1}{40 * 5} \sum_{d=1}^{40} \sum_{j=h-1}^{h+4} P_{load,d,j} \tag{21}$$

3.3.3. The bidding strategy

The bidding strategy is named "Merchant/reliability", merchant being the part of the strategy when a lower award rate is accepted for potentially higher economic benefit, while the reliability strategy aims to assure that the bid is awarded by reducing the potential remuneration. In the strategy, the BESS bids both upward and downward capacity at different prices coherent with the SoC. The reliability strategy assumes that being awarded helps the battery SoC management. Indeed, in case the battery is far from saturation and depletion (SoC is between a lower and an upper threshold SoC_{lo} and SoC $_{hi}$), the bid price is the merchant price ($€_{upMer}$, $€_{dnMer}$). Instead, if battery is close to saturation (SoC is above SoC_{hi}): the bid price is equal to the reliability price for upward reserve ($€_{upRel}$) to increase the possibility to discharge via upward provision. Eventually, if a risk of depletion is detected (the SoC is below SoC_{lo}), the price is set coherently to the reliability price for downward ($€_{upRel}$). The possibilities are shown in (22). The merchant prices are competitive prices, set equal to the average awarded price for either upward or downward service on the BM [36]. The reliability prices are worthwhile prices, set as the average awarded prices minus (for upward) or plus (for downward) the standard deviation of the average awarded prices, retrieved as output of statistical analysis on Italian BM [41]. Reliability prices are more likely to be awarded and less remunerative. Indeed, reliability prices are offered in case there is high interest in being awarded for modifying the setpoint of the battery for restoring the SoC in that direction.

$$\begin{cases} \left[€_{up}, €_{dn}\right] = \left[€_{upMer}, €_{dnMer}\right] & \text{if } SoC_{lo} < SoC\,(h-1) < SoC_{hi} \\ \left[€_{up}, €_{dn}\right] = \left[€_{upRel}, €_{dnMer}\right] & \text{if } SoC\,(h-1) \leq SoC_{lo} \\ \left[€_{up}, €_{dn}\right] = \left[€_{upMer}, €_{dnRel}\right] & \text{if } SoC_{hi} \leq SoC(h-1) \end{cases} \tag{22}$$

For performing SoC management, either a lower remuneration is accepted for discharging or a higher willingness to pay for charging is present. Merchant and reliability thresholds are shown in Table 3. We highlight the bidding strategy is ex-post the DAM. Therefore, every awarded call on ASM is remunerated at $€_{up}$ (the prosumer receives that price) or paid at $€_{dn}$ (the prosumer pays that price).

3.3.4. The ancillary services market model

The Italian ASM is a pay-as-bid market with hourly contract periods. In the approach proposed, a simplified market model is implemented to assess the award/rejection of the bid. A maximum accepted price for upward reserve ($€_{upMax}$) and a minimum accepted downward price ($€_{dnMin}$) 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 described in [42], performed on BM data retrieved from [25], for the period 2017–2019, for the products including the mFRR and RR provision. The market model receives as input the marginal prices $€_{upMax}$ and $€_{dnMin}$, and the bid prices $€_{up}$ and $€_{dn}$ only in case the respective bid quantity is larger than zero. An upward bid is awarded in case the marginal price $€_{upMax}$ is larger than the bid price, as presented in Fig. 8. Vice versa, a downward bid is accepted if the marginal price $€_{dnMin}$ is lower than the bid price (the bid price represents the willingness to pay). In case no bids are accepted, the BESS does not provide services on ASM for the relevant period. In case only one bid is accepted, this is automatically awarded, and the corresponding quantity must be delivered by the BESS for that hour. In case both bids are accepted, only one can be awarded. In this case, the awarded bid is decided based on the spread between the DAM price and the ASM price.

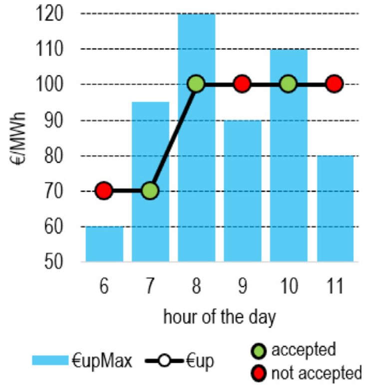

Fig. 8. Award/rejection rule for an upward bid by the ancillary services market model.

$$\begin{aligned} €_{upSpread} &= €_{upMax} - €_{DAM} \\ €_{dnSpread} &= €_{dnMin} - €_{DAM} \end{aligned} \tag{23}$$

where $€_{upSpread}$ is the upward spread, $€_{dnSpread}$ is the downward spread, $€_{DAM}$ is the DAM price (where $€_{DAM}$ is a constant). If the upward spread is larger than the downward spread, then the upward bid is awarded; otherwise, the downward bid is awarded. This is justified by the assumption that a larger spread is a symptom of a larger need for that type of regulation by the market. The bids are either awarded completely or rejected, i.e., no partial (in terms of awarded quantity in kW) award is considered. Defining two binary variables $X_{up}\,(h)$ and $X_{dn}\,(h)$ which depicts if an upward or downward bid has been accepted for hour h of the market session, the power that needs to be provided for each hour h of the market session for the mFRR service is:

$$P_{ASM}\,(h) = P_{bidUp}\,(h) * X_{up}(\mathrm{h}) - P_{bidDn}\,(h) * X_{dn}(h) \tag{24}$$

The awarded price ($€_{ASM}$) can be both positive and negative: BESS manager gets revenue for providing energy and it holds a cost for buying it, as shown in (25).

$$€_{ASM}\,(h) = €_{up}\,(\mathrm{h}) * X_{up}\,(\mathrm{h}) - €_{dn}(\mathrm{h}) * X_{dn}(h) \tag{25}$$

It is worth noting that the P_{ASM} is some kW: to cope with the minimum bid size on ASM, the single BESS should be aggregated in a VPP.

3.4. Techno-economic evaluation

The energy flows related to all the provided services are estimated, as well as the energy exchanged with the grid. Indeed, this is a twofold KPI: it is important both for the user (the lower the exchanged energy, the larger the self-consumption) and for the system (larger energy flows increase the network operating costs). The total absolute exchanged energy (E_{exch}) is the gross summation of the exchange with the grid, as can be seen in (26).

$$E_{exch} = \sum_{t=1}^{T} \left| P_{grid}(t) - P_{ASM}(t) \right| * \frac{1}{S * 3600} \tag{26}$$

The exchanged energy does not consider the energy traded on ASM, which is estimated explicitly. This is coherent with Eq. (12) and with the rationale of the control strategy: it aims to decrease the exchange with the grid (the imbalance) and at the same time to increase the provision of balancing. MFRR flows are computed separately for upward and downward regulation. The requested energy for downward regulation (E_{dnASM}) and upward regulation (E_{upASM}), are the sum of the negative and positive values of P_{ASM}, respectively shown in (27) and (28).

$$E_{upASM} = \sum_{t=1}^{N} \left| P_{ASM}(P_{ASM}(t) > 0) \right| * \frac{1}{S * 3600} \tag{27}$$

$$E_{dnASM} = \sum_{t=1}^{N} \left| P_{ASM}(P_{ASM}(t) < 0) \right| * \frac{1}{S * 3600} \tag{28}$$

The requested energy for ASM trading (E_{ASM}) is the sum of the absolute values of E_{upASM} and E_{dnASM}. Non-performance (NP) is the marker for the reliability of the provision. NP is the amount of energy that is not provided to the ASM and is penalized. Expectedly, the non-performance can be calculated as the difference between the requested ($P_{BESS\_ac\_req}$) and provided set point (P_{BESS_ac}), considering a 5% tolerance margin with respect to the set point requested by the ASM (P_{ASM}): within that margin, no penalties are foreseen [43]. It should be noted that the NP is evaluated only when a bid is accepted, i.e. $P_{ASM}(t) \neq 0$.

$$\begin{cases} P_{NP}(t) = P_{BESS\_ac}(t) - P_{BESS\_ac\_req}(t), \\ \qquad if \ \frac{\left|P_{BESS\_ac}(t) - P_{BESS\_ac\_req}(t)\right|}{P_{ASM}(t)} > 5\% \ and \ P_{ASM}(t) \neq 0 \\ P_{NP}(t) = 0 \quad elsewhere \end{cases} \tag{29}$$

Then, the overall NP (in %) is obtained for the entire analyzed period T, as the integral of $P_{NP}(t)$ over the E_{ASM}, as in (30).

$$NP = \sum_{t=1}^{T} \frac{\left| P_{NP}(t) \right|}{P_{ASM}(t)} \tag{30}$$

Lastly, a comparative economic analysis between the two control logics – SC only vs the Multiservice strategy – is proposed. In both cases, the avoided costs thanks to self-consumption (R_{SC}) are the net sum of bill cost minus injection revenues: both costs and revenues decrease if self-consumption increases.

$$R_{SC} = \left(C_{bill} * E_{withSConly} - €_{DAM} * E_{injSConly}\right) - \left(C_{bill} * E_{withMultiservice} - €_{DAM} * E_{injMultiservice}\right) \tag{31}$$

Where C_{bill} is the bill cost in €/kWh, $€_{DAM}$ is the DAM zonal price (we assume no incentive for RES injection), E_{with} and E_{inj} are the withdrawal and injection in the SC only and Multiservice case.

The gross ASM remuneration is given by the hourly bid price times the provided energy. It is a positive number (a revenue) for upward provision and a negative number (a cost) for downward provision. It is calculated for the entire period analyzed T with the respective hourly values as:

$$R_{ASM} = \sum_{h=1}^{T} €_{ASM}(h) * P_{ASM}(h) \tag{32}$$

Then, the net ASM remuneration considers the penalties for NP. The penalty (correlated with ASM prices in Italy) is arbitrarily set to a high constant value ($€_{fee}$). The final direct net revenue from the ASM is evaluated as in (33).

$$R_{ASM\_net} = R_{ASM} - NP * €_{fee} \tag{33}$$

To compare with the SC-only strategy, it must be noted that the energy exchanged on ASM could have been exchanged on the energy markets, instead. In case downward energy is provided, the net benefits come from the difference between downward prices and bill costs, where $€_{Dn} < €_{bill}$. For upward provision, the regulatory framework is relevant: the injection price could vary in case of incentives, net or gross metering. Eq. (34) presents the net benefit of ASM participation considering constant energy exchange with the grid. The withdrawal is paid at C_{bill}, while injection is remunerated at $€_{DAM}$, i.e., with gross metering (this is coherent with the regulatory framework for Italy after the beginning of the phase-out of net billing in 2022 [44]).

$$R_{ASM} = R_{ASM\_net} + \min\left(0, \sum_{h=1}^{T} P_{ASM}(h)\right) * C_{bill} - \max\left(0, \sum_{h=1}^{T} P_{ASM}(h)\right) * €_{DAM} \tag{34}$$

4. Case study

The methodology proposed in Chapter 4 is applied on four individual residential users. Data come from the H2020 inteGRIDy project [29]. In all four cases, the users are equipped with PV panels and a BESS. The users show different consumption patterns and distinct sizes of the PV plant installed. However, the BESS installed is 3 kW–8 kWh for all the users. Further optimization of battery sizing is outside the scope of the work. The BESS sizes are kept the same as the real assets.

4.1. Simulations (offline analysis)

The period investigated in the analysis is represented by 30 spring days, from the last week of April to the third week of May, 2021. Fig. 9 displays the load and PV profiles of each user for one week in May, with the following displacement: User 1 (top left), User 2 (top right), User 3 (bottom left), and User 4 (bottom right). For the sake of simplicity, this layout and time interval will be adopted for Figs. 10 and 11.

4.2. Economic parameters

The main economic parameters considered within the analysis are presented in Table 4, along with the considered sources. Most of the data are consistent with Italian data for the first half of 2021; such a choice is motivated to look for data not subject to the European rise in energy prices experienced from summer 2021 [45,46]. The BESS CAPEX considers both the battery pack and the PCS. They are based on commercial sources available for Italy at the moment of writing [47,48] and they also include the incentives in place nowadays in Italy: an incentive scheme equal to 50% of the gross invoice of every investment in energy efficiency or climate-friendly technologies [49]. Considering this incentive could limit the replicability of the study outside Italy. In

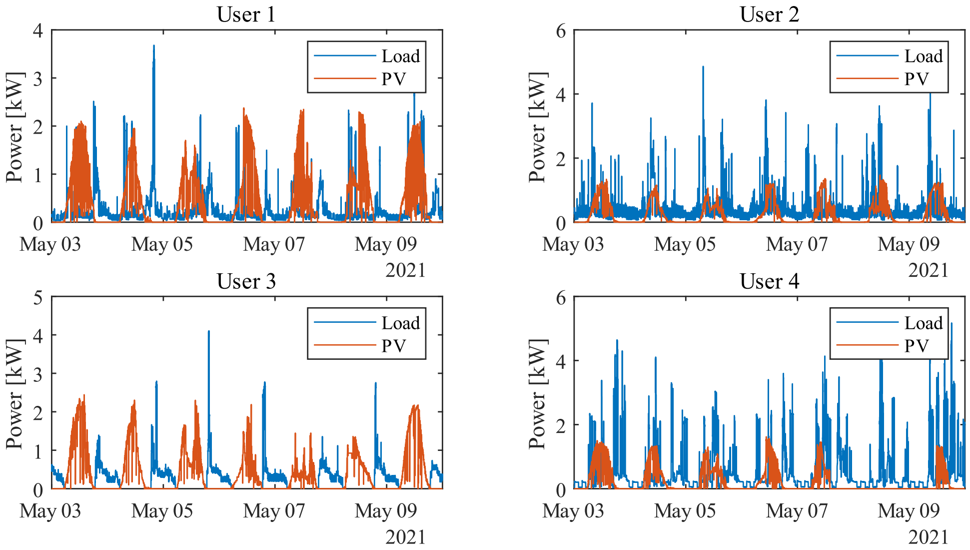
User 1
User 2
User 3
User 4

Fig. 9. Load and PV power profiles for the 30-day period and for the 4 analyzed prosumers.

Table 4
Economic parameters.

Key	Value	Source
C_{bill}	204.5 €/MWh	Italian domestic customer's data for H1 2021 [37]
P_z	66.9 €/MWh	Average zonal price for Italian DAM for H1 2021 [25]
ASM marginal prices	Variable	From a statistical analysis on Italian BM for 2017–2019, presented in [41]
€$_{fee}$	140 €/MWh	Italian ASM upward average price for H1 2021 [50]
k_e (CAPEX)	400 €/kWh	Commercial sources [33,34], also considering 50% discount on CAPEX from [49]
k_p (CAPEX)	150 €/kW	Institutional sources [51]
OPEX	5 €/kWh/y	Institutional sources [51]

Table 5
RMSE for each user in kW.

User	PV (1 h)	PV (5 h)	Load (1 h)	Load (5 h)	Cumulative (1 h)	Cumulative (5 h)
User 1	0.203	0.152	0.266	0.170	0.333	0.235
User 2	0.136	0.103	0.258	0.154	0.290	0.187
User 3	0.279	0.230	0.233	0.133	0.364	0.267
User 4	0.200	0.169	0.476	0.274	0.514	0.317

any case, it is worth considering the incentive in the case study to have quantitative results coherent with the Italian situation. Schemes such as this, based on tax expenditures, are steadily present in Italy for more than ten years ("ecobonus").[1]

4.3. The forecasting procedure

A dedicated weather forecasting service is in place to provide hourly predictions for the relevant area [42]. The weather forecast is available 4 times per day at t ∈ {00:00, 06:00, 12:00, 18:00}. The previously introduced RF algorithm is trained using 21 days of historical data and performs the prediction using 150 individual decision trees.

On the other hand, because of the lack of any significant parameters on the users that could be used for correlation with their consumption, a 40-day Simple Moving Average (SMA) procedure was adopted, estimating the overall consumption for the 5 h. At the beginning, the profile was analyzed splitting in holidays and working days. It was found that splitting the days between weekends and weekdays does not improve the accuracy (neither for the PV nor the load), thus they were not split for the forecasting procedure.

The performance of the two forecasting procedures was evaluated using the RMSE as a metric and focusing not only on the hourly errors, but also the error on the relevant period for BM (5 h). Moreover, since the final goal w to estimate the self-consumption profile of the users, the cumulative error of the two forecasting procedures was calculated as well, since it directly affects the estimation of the SC profile. The results for each user, both for the separate metrics and the cumulative one, are presented in Table 5.

The estimation error reduces when the goal is to forecast the overall profile needed for the market session. In addition, the cumulative error is always significantly lower than the sum of the individual errors of the load and PV forecast, suggesting that more often than not, the two errors counteract each other. The average cumulative RMSE of the 4 users results to be 0.25 kW, which aids towards modeling the slack that needs to be considered when offering the mFRR to the market.

Finally, Table 6 presents the cumulative 5-hour RMSE split by market session. Expectedly, we can see that the errors are the smallest during the night hours when the load uncertainties are quite small and PVs' are null. This suggests (as a future update to the proposed control strategy) that case-specific bidding strategies can be developed to have more conservative bidding during daytime hours, considering the higher estimation uncertainties and penalties due to non-performance.

5. Results and discussion

To evaluate the performance of the developed model and control strategies (SC-only and Multiservice), simulations are performed on the previously illustrated 30-day period. The following

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[1] See "Normativa Ecobonus": https://www.efficienzaenergetica.enea.it/detrazioni-fiscali/ecobonus/documenti-di-riferimento/normativa-ecobonus.html

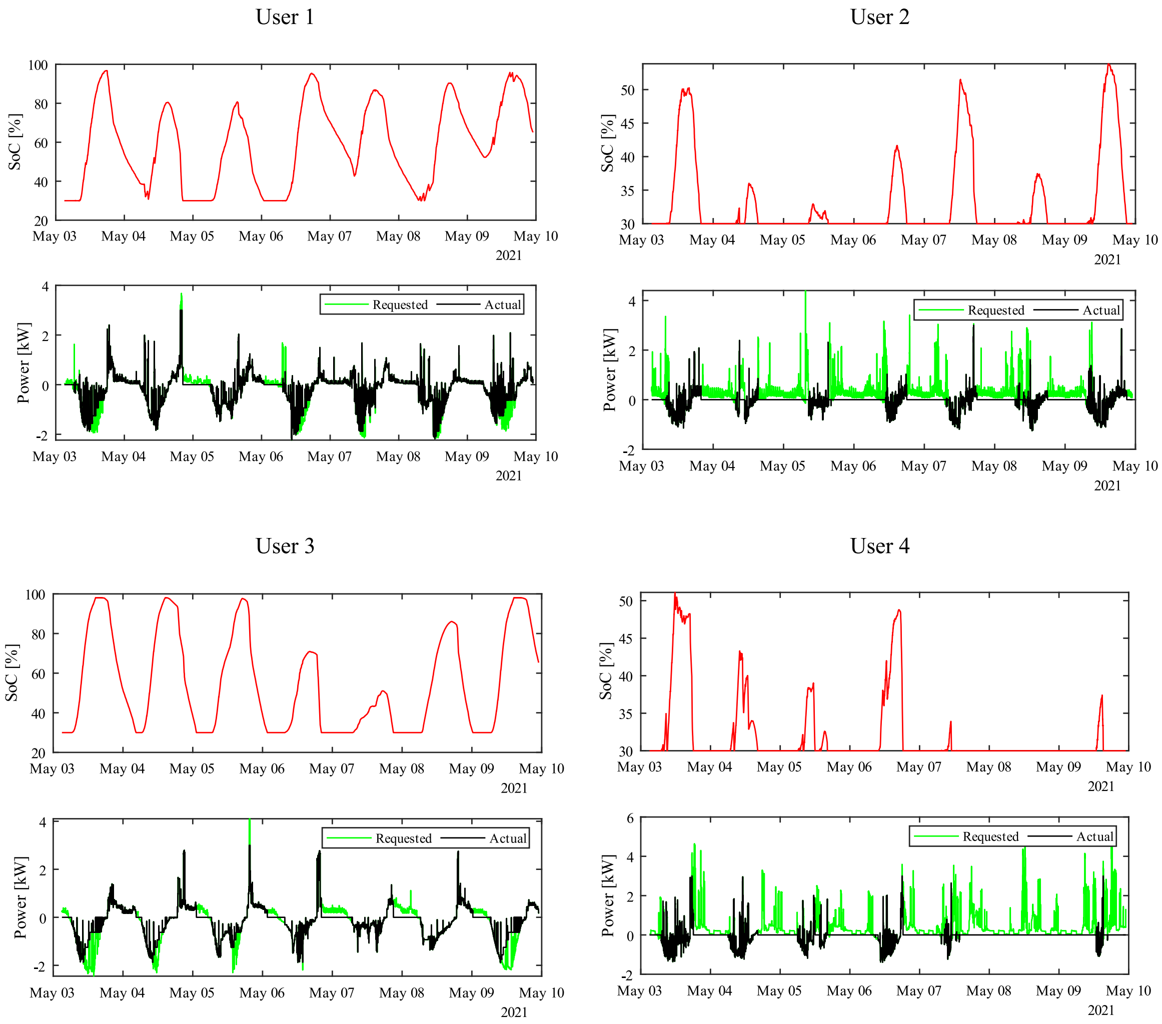

Fig. 10. Self-consumption only profiles for BESS' SoC (top red lines) and power (bottom black and green lines) for the 4 prosumers, with Sodium-based battery.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6
Cumulative RMSE per market session for each user in kW.

User	BM1	BM2	BM3	BM4	BM5	BM6
User 1	0.070	0.276	0.345	0.280	0.205	0.104
User 2	0.103	0.310	0.221	0.200	0.089	0.081
User 3	0.044	0.330	0.447	0.171	0.272	0.110
User 4	0.136	0.340	0.468	0.367	0.214	0.265

paragraphs show first the performance obtained with a high-T Sodium-based battery. Then, the results for the Multiservice strategy are compared with the ones obtained with the Li-ion battery model equipped with the same control strategy.

5.1. The reference case: Self-consumption only

The first set of simulations concerns the provision of BtM services only: the batteries are increasing the self-consumption of the 4 prosumers. A zoom of the weekly power and SoC profiles of the batteries for the 4 users is proposed in Fig. 10. As can be seen, the battery is subject to a daily cycle, with a charging path during the daytime (negative requested power) and a discharging path for the rest of the time (positive requested power). Often, the lower SoC threshold is reached, and the battery can discharge no more to feed the user's load. In this case, a gap can be seen between the power requested to the BESS ($P_{BESS\_ac\_req}(t)$) and the power that it can provide ($P_{BESS\_ac}(t)$) (see the bottom part of the diagrams in Fig. 10, with the actual power in black and the requested one in green). In some cases, a gap can be seen also during charging, if the PV production excess is greater than the nominal battery power.

Under a self-consumption strategy, SoC evolution depends on PV and load sizes: the larger the load is compared to the PV, the longer the time that the battery remains at minimum SoC, which in turn contributes to larger energy exchange with the grid. For instance, Users 2 and 4 feature a bigger load, and the SoC is depleted most of the time, obliging the prosumer to withdraw from the grid. Numbers are proposed in top part of Table 7. Indeed, the energy exchanged with the grid spans from 100 to 330 kWh: the superposition of production and consumption is limited (i.e., a limited self-consumption).

5.2. Comparative analysis of control strategies: Multiservice vs self-consumption

A second case study is devoted to the simultaneous provision of self-consumption and ancillary services provision. The control logic offers the available power and energy margins after self-consumption provision on the ancillary services market. The SoC and power profiles are shown for the 4 users in Fig. 11. As can be seen, the SoC trends become spikier, with more daily cycles with respect to self-consumption only. The provision of mFRR

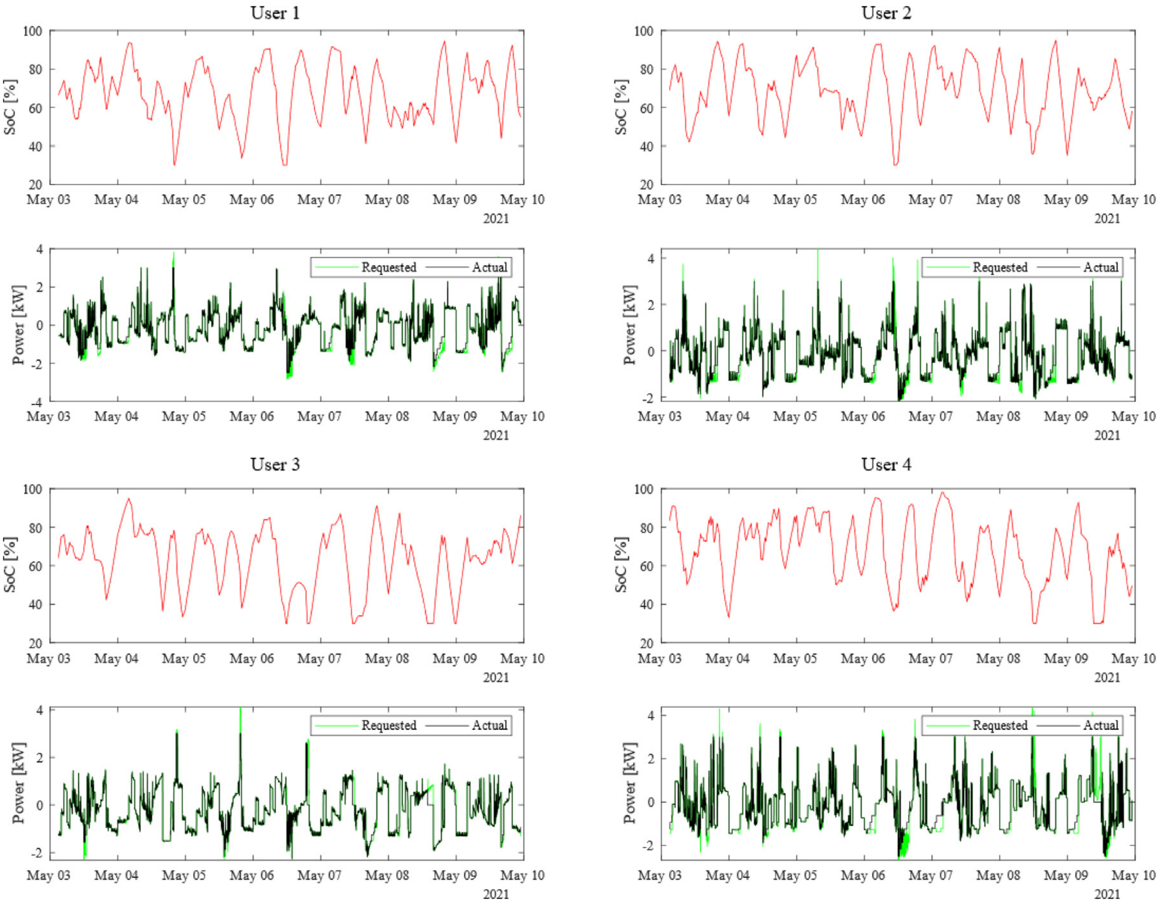

Fig. 11. Multiservice profiles for SoC (top red lines) and power (bottom black and green lines) for the four prosumers, with Sodium-based battery.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

requires either to charge (downward) or discharge (upward) at a constant power for some hours. The SoC saturation is almost always avoided since the margins are computed as in Eqs. (17), (18). Consequently, the requested and actual power profiles are almost perfectly overlapping, with minor exceptions due to the capability curve of the battery. This is because the Multiservice strategy acts as an implicit SoC management strategy [10]: the available band is larger downward in case the battery is close to minimum SoC (or it is discharging due to self-consumption), and vice versa. Therefore, the mFRR provision requests power setpoints generally opposite with respect to self-consumption, bringing back SoC towards the target (50%).

Table 7 returns a quantitative analysis of the energy flows. These are shown as the energy exchanged with the grid (either for satisfying the demand or for injecting the excess PV generation) and the energy traded on ASM (that is not considered as energy exchanged). The SoC profile generally manages to avoid saturation for all the Users, despite their different consumption intensities: indeed, in case the consumption largely overcomes the production, more downward service is offered by the Multiservice strategy, and vice versa. This can also be investigated in Table 7, where User 2 and User 4 (energy-intensive users, characterized by long time at minimum SoC in SC only case, as seen in Fig. 10) show around 50% more downward energy traded and half upward energy compared to User 1 and 3. A relevant amount of energy is traded on ASM by all the users (more than 500 kWh per month), with a nonperformance (NP) on ASM almost always below 5%. This means that a large amount of flexibility can be offered by distributed systems and provided with a decent level of accuracy (accuracy is seen as complementary to 1 of NP). On the other side, the exchange with the grid for coping with the imbalance between PV and load is drastically decreased, meaning that the Multiservice also improves self-consumption.

Finally, Multiservice – LiB case considers the presence of a LiB modeled as described in paragraph 4.1 [24]. As previously mentioned, SMC batteries are under study for a future generation of more sustainable batteries, while the LiB presents higher efficiency and lower auxiliary demand. This enhances the quantity of upward service that can be provided on ASM without depleting the energy content.

Table 8 summarizes the economic outcomes. For the SC only case, the cash flows are only related to the bill costs and the DAM revenues. Bills are estimated by considering the average bill cost for a domestic user in Italy in the first half of 2021: 20.45 c€/kWh [37]. The injection value considers the direct selling of DAM in the same period: 66.9 €/MWh (or 6.69 c€/kWh) [25]. As can be seen, all the users need to withdraw much more than they can inject, and the overall net cash flow (NCF) is always negative.

The multiservice case adds ASM net cash flows to the revenue stacking: the provision of upward service is associated to a revenue coherent with the awarded prices, estimated based on the statistical BM model developed. Oppositely, downward calls entail costs for the prosumer: battery is charging (or consumption is satisfied) by the energy absorbed via mFRR provision. Also, a penalty for NP (NPP) is considered (140 €/MWh). The net revenues are either positive or negative, according to the amount of upward and downward provisions. In any case, the bill cost shrinks thanks to the drastic withdrawal reduction. In the end, the NCF improves for all the users.

As can be also inspected by Table 7, the LiB allows to shift the traded energy on ASM towards upward energy, entailing a larger

Table 7
Monthly energy flows.

CASE	USER	Exchange with the grid (excluded ASM) [kWh]	TR up [kWh]	TR dn [kWh]	TR tot [kWh]	NP [%]
SC only	User 1	102.6	-	-	-	-
	User 2	272.2	-	-	-	-
	User 3	103.8	-	-	-	-
	User 4	338.9	-	-	-	-
Multiservice	User 1	9.1	209.5	327.3	536.8	5%
	User 2	5	100.8	422.2	523.0	4%
	User 3	16.3	280.5	317.2	597.7	3%
	User 4	8.4	85.5	506.3	591.8	11%
Multiservice - LiB	User 1	14.3	271.4	224.6	496.0	2%
	User 2	7	150.4	300.7	451.1	2%
	User 3	9.9	383.0	244.6	627.6	3%
	User 4	23.9	156.6	392.5	549.1	7%

Table 8
Monthly cash flows.

Case	User	Bill cost [€]	Inj value [€]	ASM up rev [€]	ASM dn cost [€]	ASM NPP [€]	ASM net rev [€]	NCF [€]
SC only	User 1	18.14	0.93	-	-	-	-	-17.21
	User 2	55.66	-	-	-	-	-	-55.66
	User 3	10.47	3.52	-	-	-	-	-6.95
	User 4	69.31	-	-	-	-	-	-69.31
Multiservice	User 1	0.82	0.34	19.15	9.62	3.57	5.96	5.48
	User 2	0.49	0.17	10.94	12.80	2.81	-4.67	-4.99
	User 3	0.53	0.92	23.64	9.29	2.34	12.01	12.40
	User 4	0.39	0.43	9.41	16.13	9.09	-15.81	-15.76
Multiservice - LiB	User 1	1.31	0.53	23.82	6.70	1.68	15.44	14.66
	User 2	0.35	0.35	15.71	8.51	0.98	6.22	6.23
	User 3	1.08	0.31	31.37	7.54	2.81	21.02	20.24
	User 4	1.90	0.98	14.35	12.31	5.17	-3.13	-4.05

ASM net revenue with respect to the previous case (generally, +10 € on the 30-day period, see the bottom part of Table 8). This is due to the larger efficiency and lower auxiliary demand of LiB with respect to SMC. In any case, despite the technology, the Multiservice strategy always generates a benefit on the exchange with the grid and on the net revenues with respect to SC only.

The model considers market uncertainty: Fig. 12 shows the violin plots of acceptance on the market. The offered price is shown on the x-axis and the awarded quantity on the y-axis. As seen in the left part of the picture, a lower price is offered for downward service in case there is a less available quantity (SoC is high). In this case, the merchant strategy is adopted and

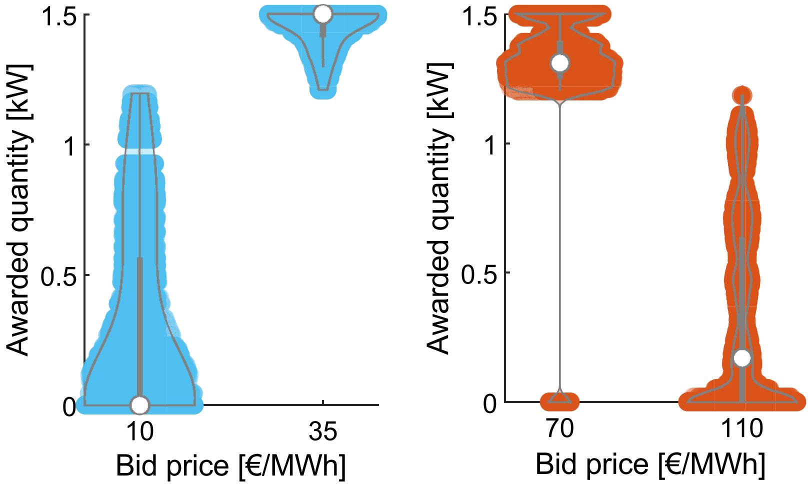

Fig. 12. Violin plots for the awarded ASM bids. In blue, the downward bids, with price (x-axis) and quantity (y-axis) awarded. In orange, the upward price and quantity.

the possibility of being rejected increases (i.e., the bid price is often lower than the minimum awarded price for that market session). Instead, in case of reliability strategy (second violin of left picture), the bids are always awarded, and the awarded quantity is around 1.2–1.5 kW (on each 3 kW battery): this means that, in case SoC is low, the bidding strategy is willing to pay a higher price to purchase energy, and the bid is usually awarded since it is very convenient for the system operator to accept that flexibility, that allows implicit SoC management. Symmetrically, for upward reserve, the "reliability" strategy bids at 70 €/MWh when SoC is close to the upward saturation limit: in this case, the bid is usually awarded, and the awarded quantity is generally high, as can be seen in the right part of Fig. 12, first violin. In case of lower SoC (see the violin to the far right), the "merchant" strategy bids at a larger price and the market model returns very often a rejection of the bid.

For 28% of the time, the 3 kW batteries can bid on the market more than 1 kW of mFRR. This can give a general indication on the potential to provide flexibility that can be achieved by domestic batteries equipped with the Multiservice strategy if this approach is scaled-up.

As suggested by the previous analyses, the Multiservice strategy seems to give economic benefits for different users. To better understand the magnitude of each user's benefit, Fig. 13 graphically proposes the comparison between SC and Multiservice's net revenues. For each User, the NCFs of the three case studies are presented and the waterfall diagram shows the share of benefits with respect to the SC only case with the SMC BESS (left bar): the second bar shows the improvement by introducing the Multiservice strategy (with the same BESS); the third one shows the benefit of considering a Li-NMC BESS (LiB); finally, the right bar shows the NCF of the Multiservice – LiB case for each User. The switch of control strategy allows always to give the greater benefit (via revenue stacking). The impact is larger for those users who have a larger consumption with respect to the PV production: User 2 to the top right and User 4 to the bottom right recover around 50 € per month, mainly thanks to the drastic decrease in withdrawal. The switch towards a LiB then provides a marginal gain (around 10 € per month), homogeneous for all the users. In the end, the larger economic benefit is shown for the energy-intensive customers (even if the NCF keeps negative for User 4). It is worth noting that in this analysis only the differential cash flows are taken into account: i.e., no CAPEX and OPEX are considered, as well as the increase in BESS decay due to the more intensive use for Multiservice strategy.

5.3. Multi-year analysis on multiservice – LiB case

To better cope with the mentioned limitations – such as the neglection of CAPEX, OPEX, and BESS life – a multi-year analysis is eventually given. The results are schematically presented in Fig. 14. The multi-year analysis compares the Multiservice – LiB case with a Reference Case where no battery is present (only PV and loads are considered). In the reference case, if instantaneous production overcomes consumption, the energy is injected at the zonal price; vice versa the energy is withdrawn at the bill price. The study case is selected for the availability of a reliable aging model for LiB [52] and for the availability of up to date (2021) CAPEX data for residential batteries in Italy. The CAPEX considered are the average of commercial sources [47,48] for a battery with E/P equal to 1 h, also considering the incentives in place in Italy at the moment of writing (50% invoice discount on the total cost of the battery) [49]. The adopted equation is the following one.

$$CAPEX = E_n * k_e + (P_n - E_n) * k_p$$

where, as presented in Table 4: k_e is 400 €/kWh, coherent with what was illustrated before; k_p is 150 €/kW, to take into account a duration of the battery different from 1 h and therefore larger or lower costs of the inverter. The OPEX are 5 €/kWh/year [51].

Besides costs, the net revenues related to bill management and ASM are considered. For bill management, the net cost variation of energy exchange in the Reference Case and in the case study is considered. By adding the battery, the injection value decreases, since the energy is absorbed and then released for self-consuming, reducing the cost of the bill, too: generally, the net economic impact is largely positive, especially for the energy-intensive users (see the green columns of User 2 and 4 in the right part of Fig. 14). The ASM net value is the sum of the upward revenues and the downward costs: it increases in case the ratio between PV production and load is larger, as can be seen by the blue columns on the left part of the figure. Generally, the impact of increased self-consumption is larger and allows to recover the CAPEX in a brief time for energy-intensive users: as can be seen by inspecting the black dotted lines, the payback time is around 5 years for User 2 and 4, much higher for User 1 and 3. It is worth noting that this level of self-consumption can only be achieved thanks to the Multiservice strategy: it helps preventing the SoC depletion issues shown in Fig. 10. BESS lifetime does not significantly impact the analysis, i.e., lifetime is larger than

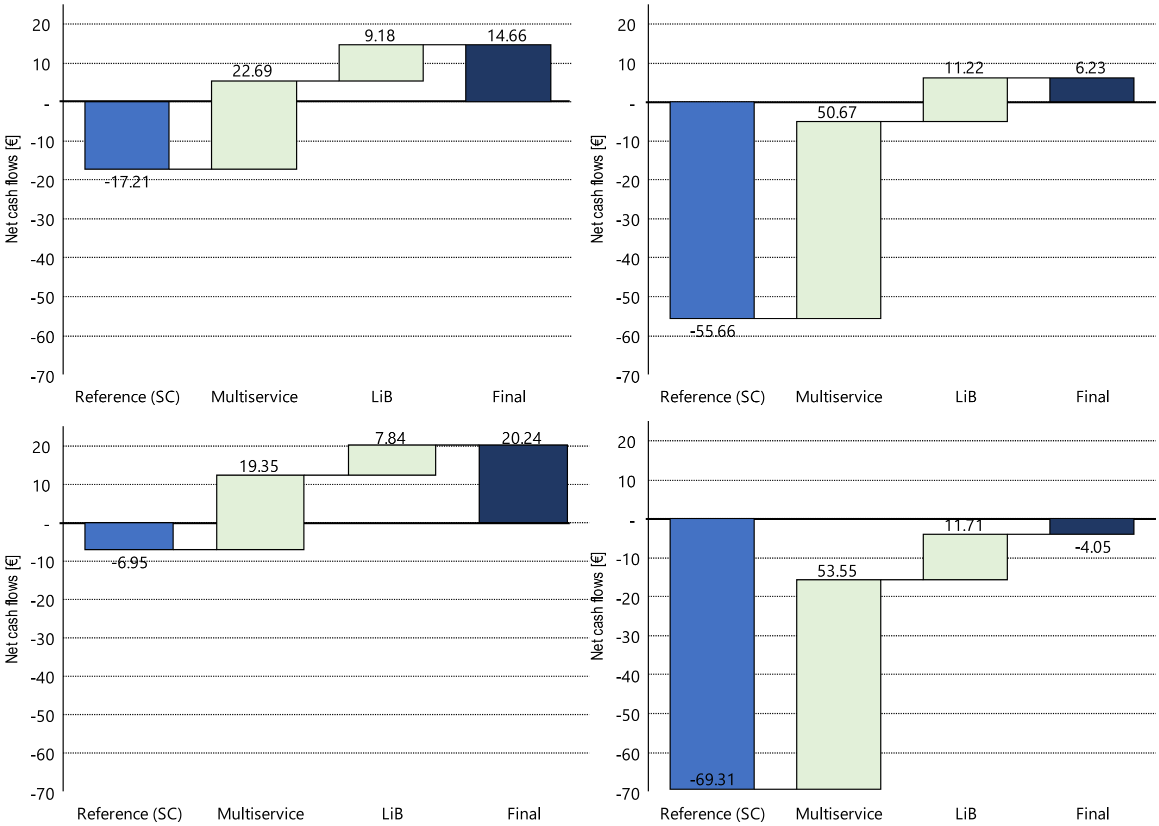

Fig. 13. Analysis of the net cash flows for the four users and the three case studies.

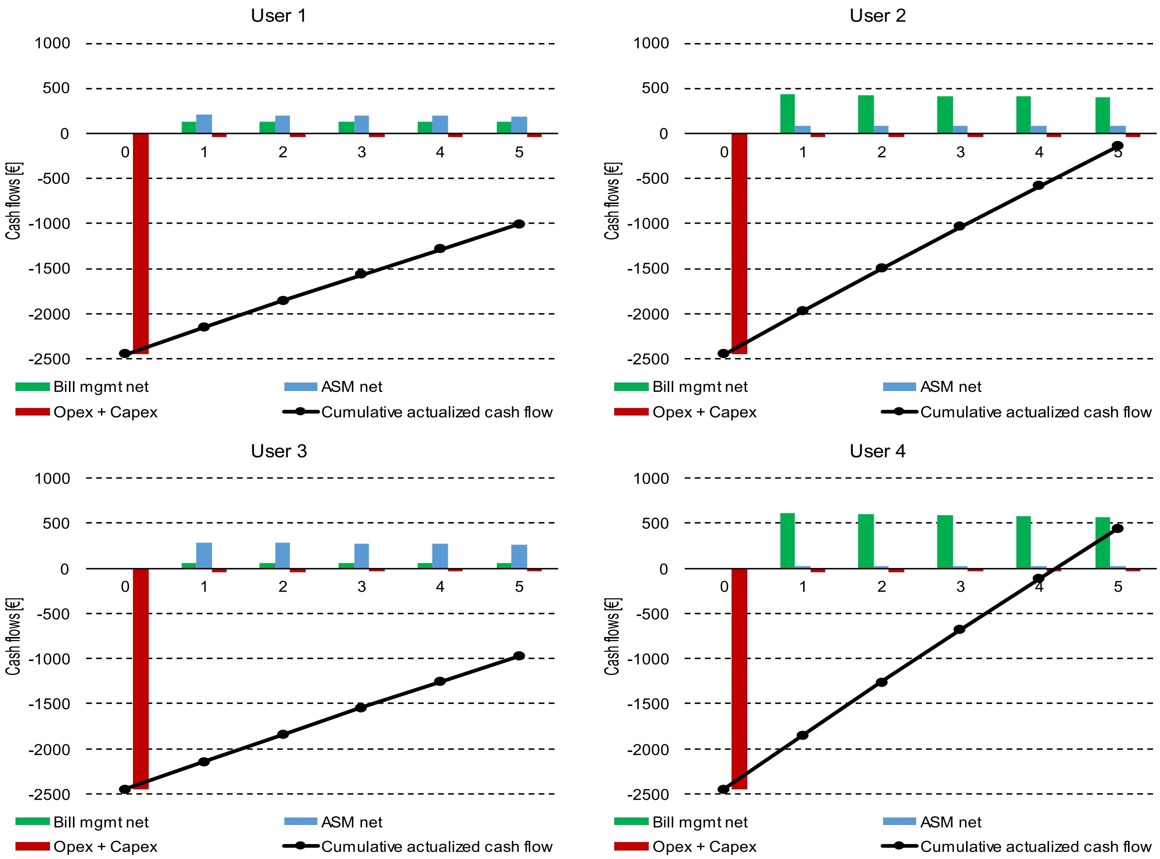

Fig. 14. Multi-year project analysis on Multiservice – LiB case.

5 years and no residual value at the end of year 5 is included. All the economic evaluation considers 2% of actualization rate.

As shown in Fig. 14 and previously discussed, the proposed revenue stacking makes profitable for energy-intensive users the investment in BESS, considering the commercial CAPEX proposed in Table 4 and in case the expected battery life is larger than 5 years.

6. Conclusions

This work presented a control strategy that can provide RES integration in a market framework and can substitute standard self-consumption routines in BESS + RES systems. The Multiservice strategy exploits the synergies between two services, drastically improving the technical and economic performance with respect to the standard, single-service routine. The strategy is simplified and applied to a replicable framework to enhance its applicability. For instance, the regulatory framework does not consider specific incentives on injected energy and the provided service is represented by a standard balancing product (as per EU regulatory definition). It is suggested that proposing this strategy as a standard can significantly help in solving the problems of increasing penetration of intermittent RES: the RES imbalances and the need for more flexibility. The positive outcomes of this study can stimulate the regulation and policymaking to foster the opening of ASMs to DERs.

The Multiservice strategy implements a dynamic service stacking providing behind-the-meter and front-of-the-meter services by a prosumer equipped with BESS and PV. Considering data of four different users, data of Italian ASM and a 30-day framework, the techno-economic performance is estimated, with KPIs concerning the economics and the quality of service provided to the system. A bidding strategy named "merchant/reliability" is tested: it bids (i) at a very convenient price when the state-of-charge of the battery is close to saturation, to prevent it and increase reliability; (ii) at a merchant price in case the risks of SoC saturation are low, to increase economics. The outcomes of the bids are checked against a statistical model of the Italian Balancing Market, that returns the outcome of the bid (i.e., awarded or rejected). It is worth noting that BESS enables the ASM participation for the PV prosumer. Indeed, in the case in which a BESS is not present, a drastic demand response strategy should be implemented.

Reliability in the provision of ancillary services is generally above 95%. The energy exchange with the grid was decreased by 90% in the case of Multiservice with respect to self-consumption only. The payback time of a Li-ion domestic battery is around 5 years in case of energy-intensive users, whereas the decrease in withdrawn power at the DAM price, thanks to the provision of downward service, drastically shrinks the costs.

The limitations of the study rely in considering a national framework for the electricity markets and incentives in place. It is well known that different countries have different specificities in ancillary services trading [53]. Additionally, the use of a DAM price ante-gas crisis [45] can limit the applicability of the results to post-2022 framework. In any case, the previous limitations are partially coped by considering a standard balancing product (thus, EU framework) and the DAM vs ASM price spread (also qualitatively valid post-2022). Moreover, the state-of-health of battery has not been considered: the adoption of a 10-years project framework is to guarantee the return on investment likely occurs before the end of battery's life [54]. Additionally, no optimization is performed in the control strategy: the self-consumption always has the priority on the ASM participation. This limitation is motivated by the specific national framework under analysis in which small customers have higher profit margin by reducing their bill, rather than participating to markets via a BSP.

Further studies could investigate different incentive and tariff schemes (for instance, what happens in case there is a net metering system or other incentives on PV injection) and can perform some sensitivity analysis with a specific focus on the cost of batteries and the outcome of the ASM (e.g., what happens in case the rate of awarded bids on total is much lower). Moreover, a simultaneous optimization between prioritizing self-consumption and ASM participation can be performed in order to reduce the bias introduced by the underlying national framework. Of course, this would require an accurate forecast of not only the local generation and load profiles, but also the behavior of the market. Additionally, a BSP model should be added to assess the effect of the aggregation of multiple batteries on the reliability and the volume of flexibility that can be provided.

One possible direct application of the results reported within this paper is to perform a nationwide analysis on the opportunities of household BESS participation to the ASM. Knowing that in Italy, the mFRR needs are 500 MW at peak and 350 MW off-peak [55]. For example, the analysis performed within this paper showed that one third of the capacity of the battery can be reliably available for market participation in a significant number of hours. One direct application of the results would be to perform a linear extrapolation to analyze the interaction between number of BESS and the percentage of the ASM's request that could be supplied, whereas future studies can focus on a probabilistic approach that can take into consideration the various behaviors and availability of prosumers. Following the linear extrapolation logic and given that as per 2022 data, 280 MW of small-scale batteries (P_n < 6 kW) are already installed in Italy [56], it can be estimated that they could provide around 19% of the peak needs for mFRR when controlled with the multiservice strategy proposed within this paper.

CRediT authorship contribution statement

Giuliano Rancilio: Conceptualization, Methodology, Visualization, Writing – original draft. **Aleksandar Dimovski:** Data curation, Software, Writing – review & editing. **Filippo Bovera:** Conceptualization, Methodology, Software. **Matteo Moncecchi:** Conceptualization, Investigation, Formal analysis. **Davide Falabretti:** Conceptualization, Project administration, Writing – review & editing. **Marco Merlo:** Supervision, Conceptualization, Methodology, Writing – review & editing.

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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